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January 1935

FACTORS AFFECTING THE PERFORMANCE OF HOSIERY ON THE HOSIERY-TESTING MACHINE

By Herbert F. Schiefer and Richard S. Cleveland

ABSTRACT

The results which have been obtained on the hosiery-testing machine since the publication of Research Paper RP679 are discussed. It is shown that laundering, dyeing, aging, finishing, and construction all have a great effect on the distensibility, elasticity, and endurability of the stockings on repeated distention. The information given furnishes a necessary background for the use of the machine for hosiery testing and demonstrates its suitability for researches in knitting, degumming, dyeing, finishing, aging, laundering, redyeing, and refinishing of hosiery.

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I. INTRODUCTION

The need for a comprehensive study of the various factors which may affect the performance of hosiery on the hosiery-testing machine of the National Bureau of Standards was indicated in Research Paper RP679.[1] Although it has not been possible to study hosiery manufactured under strictly controlled conditions and sampled at the successive stages in the process, a large number of women's full-fashioned stockings have been tested. These tests provide information on the effects of laundering, dyeing, aging, finishing, and construction on the performance of the stockings on the machine.

The purpose of this paper is to summarize the results of these tests and thus furnish a necessary background for those who would use the machine for hosiery testing.

[1] Herbert F. Schiefer and William D. Appel, *Hosiery-testing machine*. BS J. Research, 12, 543–49 (1934) RP679.

II. TEST PROCEDURE

A standardized laundering treatment was made the first step in the test procedure because it is customary to launder stockings frequently, and because stockings may give very different results when tested on the machine before and after laundering. This was shown in the previous paper and is confirmed further along in this one.

The stocking to be laundered was placed in a pint jar containing 200 ml of soap solution at 100° F. The soap solution contained 0.5 percent of "neutral" soap [2] dissolved in distilled water. The jar was agitated for 30 minutes in a Launder-Ometer.[3] The stocking was removed from the jar and rinsed in 4 changes of water at 100° F. The excess water was removed by centrifuging and the stocking dried on a hosiery form in a current of air at room temperature.

The hosiery-testing machine and the test procedure given in Research Paper RP679 [1] were used.

The curves plotted by the hosiery-testing machine show the load necessary to distend the upper part of the leg of the stocking to any extent between a minimum and maximum circumference, 13.3 and 21.3 inches in these tests, for a series of loading and unloading cycles. They give a complete record of the ability of the stocking to distend, its recovery after distending to the maximum circumference, and the change in these characteristics on repeated distention.

It is neither convenient nor necessary to use the entire series of curves or in fact the entire curve for any 1 cycle in expressing the essential results of a test. For example, an examination of the curves shows that the circumference, at a load of 30 pounds, taken from the loading curve in the first cycle of test is a criterion of the ease with which the stocking can be distended. In this paper this characteristic is called the "distensibility" of the stocking and the circumference in inches at a load of 30 pounds in the first cycle of the test is taken as the measure of distensibility. The maximum load on the stocking in the first cycle of test is also reported, since it may be of interest.

Similarly, the algebraic difference between the circumference of the stocking at a load of 30 pounds in the first cycle and the circumference at a load of 10 pounds in the two-hundredth cycle is taken as the measure of the tendency of the stocking to recover its original circumference after repeated loading, here called the "elasticity" of the stocking.

The number of cycles of the test required to produce a failure, that is, a hole in the stocking, is taken as the measure of "endurability" of the stocking.

By looking at the load-elongation curves of the first and two-hundredth cycles one can tell immediately whether or not a stocking has high or low distensibility and elasticity. Excellent examples are shown by the curves in B of figure 9, in which the solid curves represent a stocking having high distensibility and elasticity and the broken curves represent one having low distensibility and elasticity. In the former the curve for the first cycle rises rapidly as the load is increased and the curve for the two-hundredth cycle remains relatively close to the curve for the first cycle. Because of its high distensibility

[1] See footnote 1, p. 1.

[2] Federal Specification P-S-566.

[3] In the Launder-Ometer the jar is attached to a horizontal shaft with the base of the jar toward the shaft 2 inches from the center of rotation. The shaft is rotated at a speed of 40 to 45 rpm. The temperature is maintained constant by a water bath in which the jar is rotated.

this stocking can accommodate itself readily to the shape of the leg of the wearer without creating large stresses in the fabric, and because of its high elasticity it continues to fit the leg with use. In the latter the curve for the first cycle rises slowly as the load is increased and the curve for the two-hundredth cycle is separated considerably from the curve for the first cycle. Because of its low distensibility this stocking causes binding on the leg of the wearer and creates large stresses in the fabric, and because of its low elasticity it ceases to fit the leg with use. The endurabilities of the stockings are obtained from the counter on the machine and not from the load-elongation diagram.

The individual calibrations of the hosiery-testing machine over a period of 6 months check each other very closely. The uncertainty in the load at 10 pounds is less than 0.5 pound and at 100 pounds less than 2 pounds. The uncertainty in the circumference is less than 0.1 inch. Variations in the load-elongation diagrams between stockings, which are considerably greater than these values, must be attributed to actual differences between the stockings.

III. EFFECT OF LAUNDERING

It is obvious that the method of laundering, the materials used, and the manner of drying after laundering would have an appreciable effect on the behavior of the stockings on the machine and probably in actual use. Stockings laundered by the ordinary home method without boarding were found to behave differently from stockings laundered in accordance with the procedure used in this study. A stocking which was boarded and dried at elevated temperature had a harsher feel and a lower endurability than a similar stocking which was boarded and dried at room temperature. An extensive study of the effects of these factors was not made in this investigation. It is a fruitful field for future studies. In this paper the effect produced by laundering stockings in accordance with the procedure described in section II, is discussed.

The following discussion is based upon tests made on 89 pairs of stockings obtained from 13 hosiery mills. The stockings were knit according to definite construction specifications from 3-, 4-, 5-, and 7-thread silk yarn on 42- and 45-gage full-fashion knitting machines. Approximately one-half of them were knit with 6 more courses per inch than those of the other half. The specifications did not require that the stockings from the different mills should be degummed, dyed, and finished by the same procedure.

One stocking of each pair was tested as received from the mills. The other stocking of each pair was laundered and then tested. In 45 pairs the endurability of the unlaundered and laundered stockings was greater than 1,000 cycles, while in 15 pairs the endurability of the unlaundered and laundered stockings was less than 1,000 cycles. In 21 pairs the endurability of the unlaundered stockings was less than 1,000 cycles and of the laundered stockings it was greater than 1,000 cycles, while in the remaining 8 pairs the opposite was found.

That the same laundering treatment does not have the same effect on all stockings is clearly indicated by these results and by typical curves of 4 pairs shown in figure 1. The 4 pairs were obtained from 4 different hosiery mills, but were knit according to the same con-

struction specification, namely from 4-thread silk yarn on 42-gage knitting machines with 42 courses per inch.

The laundering treatment did not have an appreciable effect on the behavior of the stockings represented by the curves in A and B of figure 1. The curves in A are for a pair in which the endurability of both stockings was greater than 1,000 cycles. The curves in B are for a pair in which it was less than 200 cycles for both stockings

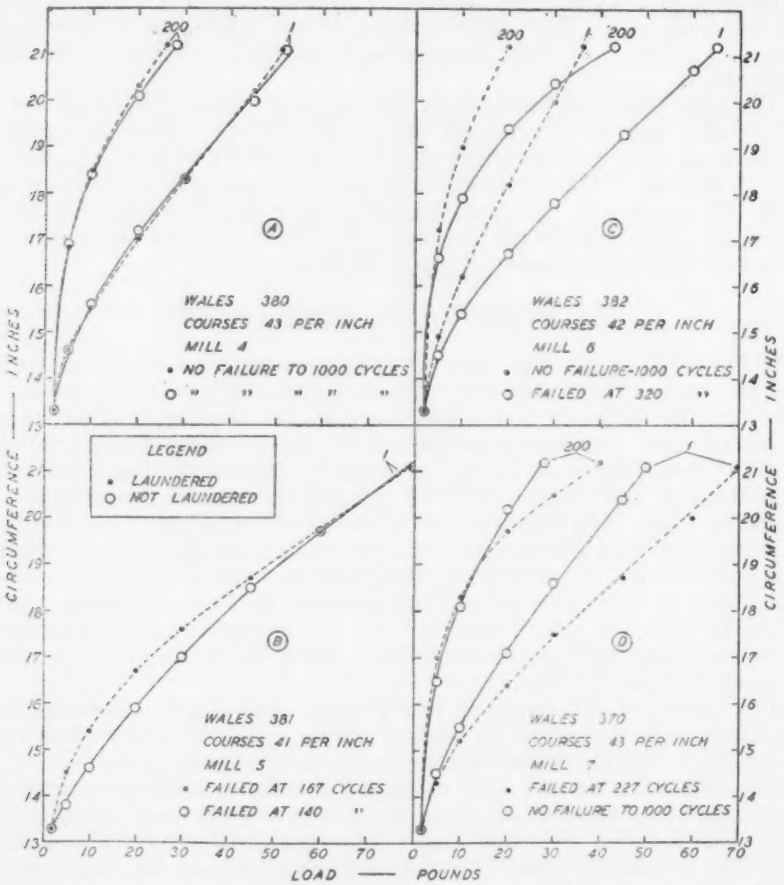

FIGURE 1.—*The effect of laundering on the performance of 4 pairs of stockings.*

These stockings were knit on 42-gage knitting machines from 4-thread silk yarn. The total number of wales exclusive of the seam, the courses per inch, and the number of cycles of test are indicated in the chart. The numbers on the curves indicate the loading cycle.

The laundering treatment did have a great effect on the behavior of the stockings represented by the curves C and D of figure 1. The effect shown in C, however, is the opposite from that shown in D. In C the endurability of the unlaundered stocking was 320 cycles and for the laundered stocking it was greater than 1,000 cycles. In D the endurability of the unlaundered stocking was greater than 1,000 cycles and for the laundered stocking it was 227 cycles.

The effect of laundering probably depends chiefly upon the treatments of the stockings after they are knit, since these stockings were

all knit according to the same construction specification. This conclusion is confirmed later in this paper.

The difference in the curves for stockings which have an endurability greater than and less than 1,000 cycles is very striking and should also be noted in the subsequent figures. In general a stocking with an endurability less than 1,000 cycles has less distensibility and elasticity than a stocking with an endurability greater than 1,000 cycles.

IV. EFFECT OF DYEING AND AGING

Two series of stockings, one degummed and the other degummed and dyed, were obtained for this study. The stockings were all knit on 1 knitting machine using the same construction and the same lot of silk. There were 48 stockings, 24 of which were knit simultaneously on the machine. All of the stockings were degummed simultaneously and one-half of the degummed stockings were then dyed simultaneously. The stockings for each series were stated to be as nearly alike as practicable in ordinary manufacturing.

Part of the degummed and of the dyed stockings were tested on the hosiery-testing machine 3 days after they had been received at the Bureau. The remaining stockings were tested approximately 20 days after they had been received. During this period the stockings were continuously exposed to the conditions prevailing in the room of constant temperature and relative humidity. Some of the stockings which were tested at the latter period were laundered before testing.

The results for the individual tests on the unlaundered stockings are given in figure 2. They show that differences between stockings stated to be manufactured as nearly alike as is practicable in the industry can be measured on the hosiery-testing machine. The difference between individual stockings with respect to the maximum load of the first cycle may be as large as 20 percent and with respect to the distensibility may be as large as 5 percent. These differences are at least 10 times as great as the uncertainty in the calibration of the machine. They may be due to a number of causes, such as variations in the silk yarn, which are known to be appreciable, variations between sections of the knitting machine, variations in the tensions on the yarn, and variations in uniformity of degumming, dyeing, and finishing, and variations in boarding. Since the differences in the above results may be caused by several of these variations, these data do not lend themselves to a determination of the factors which caused the observed differences. For such a study a more extensive series of stockings should be knit by deliberately varying 1 factor at a time. This study may be well worth while undertaking since a sensitive test is now available. For the present paper the discussion is confined to the effect of those factors which can be shown to have caused large variations.

The effect of dyeing on the stockings is indicated by the difference between the average curves, A and C for stockings tested 3 days after being received, or B and D for stockings tested approximately 20 days after being received. The effect of aging on the degummed stockings is shown by the difference between the average curves A and B, and on the dyed stockings by the difference between the average curves C and D. The average distensibility, elasticity, endurability, and maximum load of the first cycle are given in table 1.

These data bring out 3 interesting facts, namely: (1) That the hosiery-testing machine is sufficiently sensitive to measure differences which occur in hosiery manufactured to be as nearly alike as practicable; (2) that dyeing decreased the distensibility, elasticity, and endurability of degummed stockings; (3) that aging decreased the distensibility, elasticity, and endurability of both the degummed and the dyed stockings.

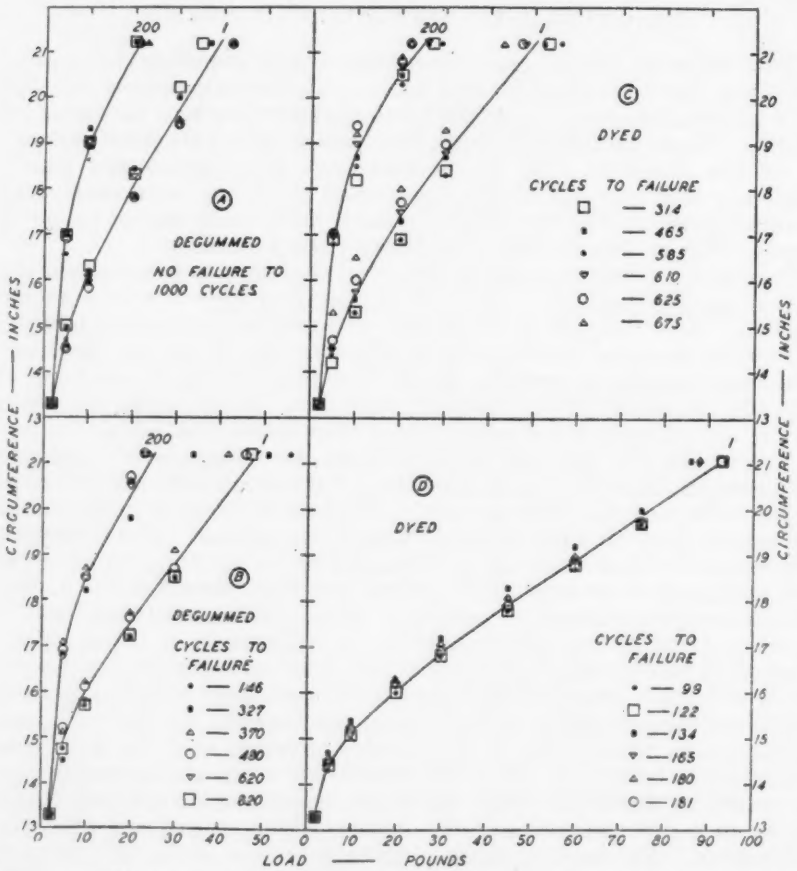

FIGURE 2.—*Variations in results for series of stockings of the same constructions taken from the same lots.*

All of the stockings represented in this figure were made at the same time by 1 manufacturer and were degummed in the same bath. Six stockings in each of the groups listed below were tested and the results for individual stockings are indicated by the symbols. Data for the first loading cycle are given and for the two-hundredth loading cycle when failure occurred after 200 cycles of test. The numbers on the curves indicate the loading cycle. A. Degummed stockings, tested 3 days after being received. B. Degummed stockings, tested approximately 20 days after being received. C. Degummed and dyed stockings, tested 3 days after being received. D. Degummed and dyed stockings, tested approximately 20 days after being received.

Tests on 2 similar series of stockings which were obtained from a second mill confirmed the results given above.

The effects of dyeing, aging, and laundering on all of the stockings from these 2 mills are shown very clearly in figure 3 and in table 1, where the average results are given for the various conditions. It is

apparent that conclusions 2 and 3 are confirmed by these results for the stockings from the 2 mills. These data, however, bring out other interesting facts which will be discussed more fully.

TABLE 1.—*Results showing the effect of dyeing, aging, and laundering on the performance of stockings from mills 1 and 2*

Mill number	Condition of stocking	Time elapsed between receipt and testing	Number of stockings tested	Endurability; cycles to failure [1]	Maximum load in first cycle	Distensibility; circumference at 30 pounds in first cycle	Elasticity; circumference at 30 pounds in first cycle minus circumference at 10 pounds in two-hundredth cycle
		Days			*Pounds*	*Inches*	*Inch*
1	Degummed	3	6	1,000+	40	19.7	0.7
1	do	20	6	460	48	18.7	.2
1	Degummed and laundered	20	11	777	52	18.2	−.2
1	Dyed	3	6	546	50	18.8	0
1	do	20	6	147	90	16.9	
1	Dyed and laundered	20	10	470	58	18.0	−.6
2	Degummed	3	1	1,000+	56	18.6	.6
2	do	20	6	560	65	17.8	.1
2	Degummed and laundered	20	8	1,000+	50	18.6	.3
2	Dyed	3	4	133	74	17.6	[2] −1.4
2	do	20	6	88	79	17.2	
2	Dyed and laundered	20	10	1,000+	48	18.8	.7

[1] Tests were not continued beyond 1,000 cycles.
[2] Value is for the one hundred and thirty-third cycle.

The great difference in the results for the unlaundered stockings when tested 3 and approximately 20 days after being received from the mills was somewhat surprising. This difference is real, however, and must be attributed to some chemical or physical change in the silk.

Analysis of the silk for ammonia nitrogen and determinations of the pH of aqueous extracts of the silk appeared to indicate that the silk was not affected chemically.

The lapse of time, 17 days, between the tests may have permitted the yarns, which are plastic immediately after degumming, to become set, that is more rigid, and therefore less free to bend and to move one on another. This physical change could cause the difference which has been observed. This explanation appears logical inasmuch as the same effect was observed for the stockings of different constructions obtained from 2 different sources. It seems plausible also because laundering appears to have eliminated, at least partially, the difference observed.

If set of the yarn accounts for the difference observed in the above tests, then it is probable that a difference could have been observed in the yarn after unravelling it from the stockings. Unfortunately this marked effect of aging was not anticipated. It was impossible, therefore, to make tests on the yarns. It is probable that the yarn from an aged stocking would have shown different elastic properties under low loads than the yarn from an unaged stocking.

It is probable that the effect of aging would vary with a number of factors such as the amount of gum left on the silk, the amount and

the kind of finishing materials put on the yarn, the dyeing process, the atmospheric conditions during aging, and the duration of the aging period. An extensive and systematic study of the effects of these factors should be made. The effect of aging can be partially eliminated by laundering and probably can be minimized by a proper finishing treatment after dyeing and proper conditions of storing.

It is to be further noted that the records of the dyed unlaundered stockings from mill 2 show the reversal effect discussed in Research Paper RP679. That is, the maximum load decreases for a few cycles and then increases and finally becomes greater than for the first cycle

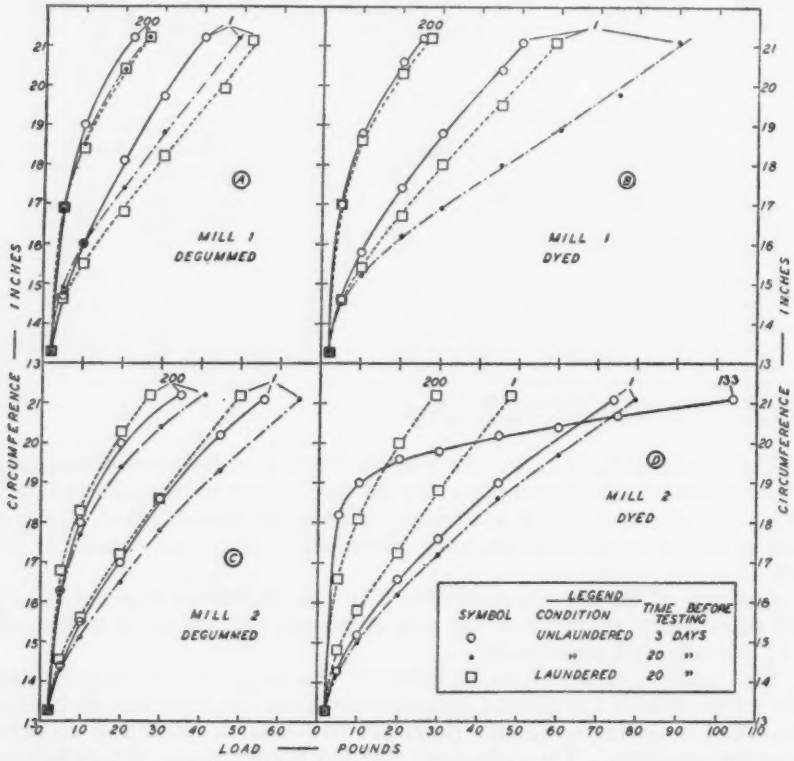

FIGURE 3.—*Effect of dyeing, aging, and laundering on the performance of stockings*

The numbers on the curves indicate the loading cycle.

The first and one hundred thirty-third cycles drawn in D of figure 3, show this reversal effect. Typical test records of stockings which do and which do not show the reversal are shown in figure 4. The endurability of stocking A, which shows the reversal, was 115 cycles. Stocking B did not exhibit the reversal and had an endurability greater than 1,000 cycles. Photographs of parts of these stockings after test are shown in figure 5. The stocking at the top showed the reversal while the stocking at the bottom did not.

When stockings which exhibited the reversal effect were tested, there was a very perceptible "grinding" noise produced by the movement and stretching of the silk yarn. The yarn became very fuzzy,

FIGURE 4.—*Typical test records of stockings which do and which do not show the reversal effect.*

Stocking A, which shows the reversal, failed at 115 cycles; while stocking B did not fail in 1,000 cycles. The curves shown in this figure are not plotted on a rectangular system of coordinates.

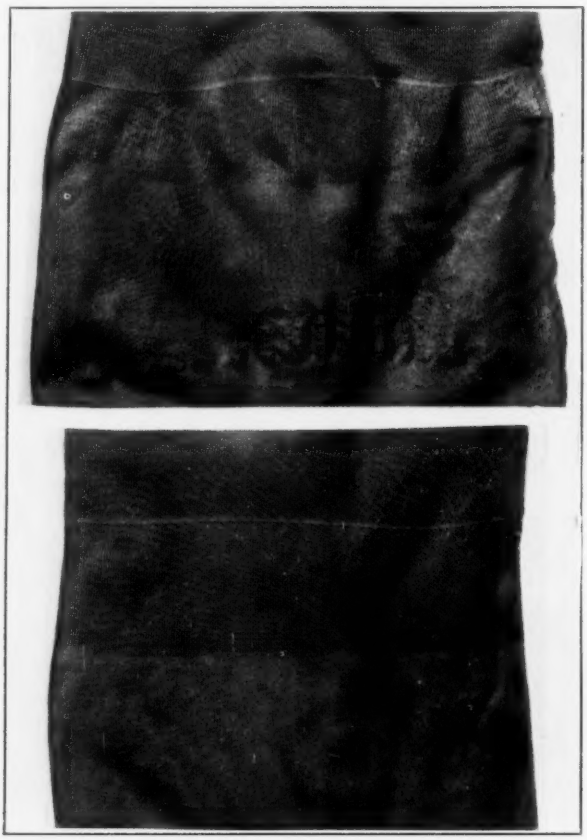

FIGURE 5.—*Appearance of stockings after test.*

The stocking shown at the top is one which exhibited the reversa leffect and failed at 115 cycles. The stocking at the bottom is one which did not show the reversal and which did not develop failures in 1,000 cycles.

the fabric became puckered, and the elasticity of the stockings decreased, i. e., they became badly deformed or baggy. It is probable that the friction between the silk filaments of the yarns increased during the test and accounted mainly for the increase in the maximum load observed for each succeeding cycle to failure.

These stockings which exhibited the reversal effect when tested before laundering behaved quite differently when tested after laundering. There was no reversal of the curves and there was no perceptible noise during the tests. The endurability was greater than 1,000 cycles, the silk yarn did not become fuzzy, the fabric did not become puckered, and the elasticity of the stockings did not decrease, i. e., they did not become badly deformed or baggy. It may be concluded, therefore, that the reversal effect observed in these stockings is produced by the particular finish given to them. This conclusion has recently been confirmed by tests on other stockings.

The results discussed in this section show the effect of dyeing, aging, and laundering on the behavior of these particular series of stockings. The effect of laundering on these stockings was to increase the distensibility, elasticity, and endurability, and probably confirms the claim which many women have made, namely, that they get better service from some of their stockings if they launder them before wearing. The utility of some finishes on stockings is questionable, particularly so when the effect is removed in the first laundering.

V. EFFECT OF FINISHING

In order to demonstrate whether or not the effect of different finishes could be determined with the hosiery-testing machine 3 groups of stockings were obtained from mill 3. There were 5 pairs in each group, each pair having been given a different finish. The stockings of a group were all of the same construction. The 3 groups differed, however, in construction, including variations in the gage, in the number of courses per inch, and in the number of threads in the silk yarn. One stocking of each pair was tested as received, while the other stocking was laundered before being tested.

TABLE 2.—*Results showing the effect of 5 finishes on similar stockings*

Finish number	Condition of stocking	Number of stockings tested	Endurability; cycles to failure [1]	Maximum load in first cycle	Distensibility; circumference at 30 pounds in first cycle	Elasticity; circumference at 30 pounds in first cycle minus circumference at 10 pounds in two-hundredth cycle
				Pounds	*Inches*	*Inch*
1	Unlaundered	3	120	85	17.3	
2	do	3	286	74	17.1	−0.6
3	do	3	672	61	17.8	.3
4	do	3	728	77	17.5	.2
5	do	3	1,000+	57	18.3	.3
1	Laundered	3	960	71	17.3	−.8
2	do	3	1,000+	49	18.6	.2
3	do	3	1,000+	47	18.8	.2
4	do	3	1,000+	62	17.8	−.3
5	do	3	1,000+	54	18.4	−.1

[1] Tests were not continued beyond 1,000 cycles.

The tests showed a marked difference between the finishes. The effect of differences between the constructions was small, probably because the several factors which were varied in the construction had compensating effects. The results are given in table 2 in which the values represent the averages for each finish on the 3 constructions. The effects of each finish and of laundering are clearly indicated. The finish has a greater effect on the unlaundered stockings than on the laundered stockings. The curves for the laundered and unlaundered stockings of finishes 1 and 5 are shown in figure 6. They represent the extreme effects of the 5 finishes.

A number of compounds are being sold to the consumer for treating stockings in the home to make them more durable. Aluminum

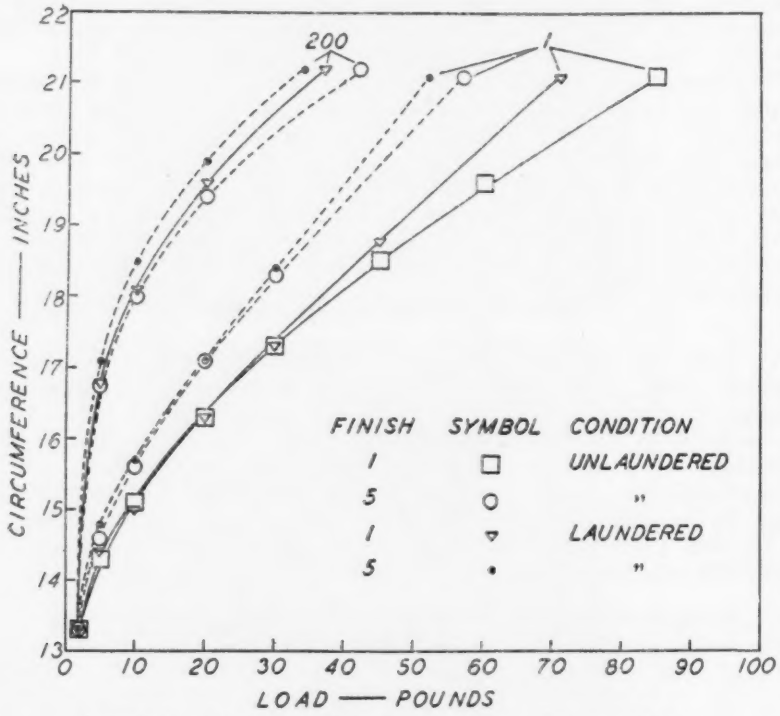

FIGURE 6.—*The effect of finishes 1 and 5 on similar stockings.*

The numbers on the curves indicate the loading cycle.

sulfate has been used for this purpose. It forms an insoluble aluminum soap on the yarn. In order to determine the effect of a known finishing treatment, 8 pairs of stockings were treated with aluminum sulfate and soap as follows. The stockings were laundered according to the method previously described. One stocking of each pair was then immersed for 30 minutes in a solution of aluminum sulfate at 100° F. This solution was prepared by dissolving 2 teaspoonfuls of aluminum sulfate in ½ pint of water. This amount of solution was sufficient for treating 2 stockings. After this treatment the stockings were dried at room temperature without boarding. They were then washed very gently for 5 minutes in a beaker containing

0.5 percent of soap solution at 100° F. The soap solution and procedure for rinsing and drying prescribed for laundering were used.

The results are shown in figure 7. In A, B, C, and D of figure 7 the effect of this treatment is shown on stockings knit from 2-, 3-, 4-, and 7-thread silk yarn, respectively, in which the endurabilities of the untreated stockings were less than 1,000 cycles and the elasticities were low. The treated stockings of these 4 pairs had endurabilities greater than 1,000 cycles and the elasticities were high. In each pair there were great differences between the curves of the treated and of the untreated stockings.

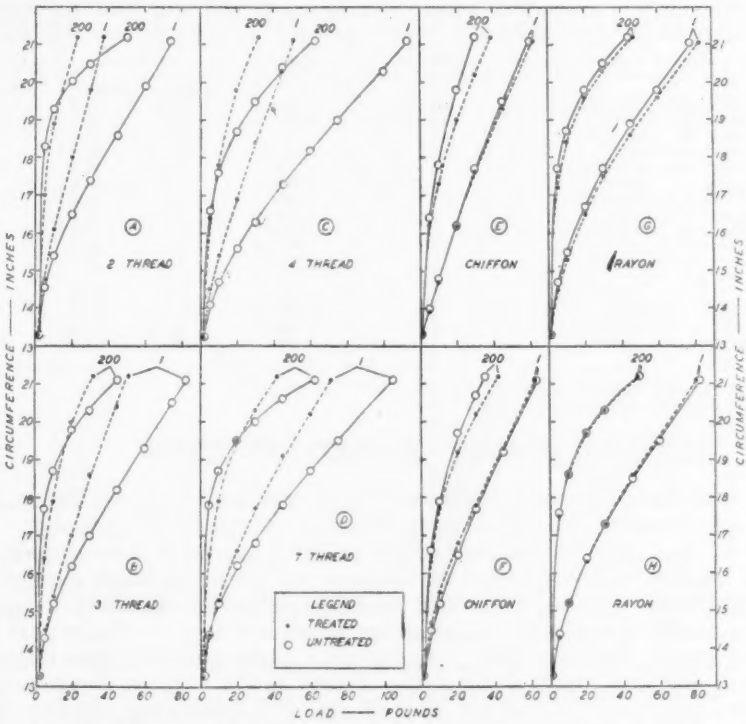

FIGURE 7.—*The effect of finishing stockings of different constructions with aluminum sulfate and soap.*

The numbers on the curves indicate the loading cycle.

In E and F of figure 7 the effect of this treatment is shown on 3-thread chiffon silk stockings in which the untreated stockings had endurabilities greater than 1,000 cycles. The endurabilities of the treated stockings of these 2 constructions were also greater than 1,000 cycles. The treatment appears to have increased the elasticity of these stockings slightly. (See table 3.)

In G and H of figure 7 the effect of this treatment is shown on 2 pairs of service-weight rayon stockings in which the untreated stockings had endurabilities greater than 1,000 cycles and also had low elasticities, i. e., they became baggy in the test. The treatment had no effect on the rayon stockings.

The results of this treatment on the 8 pairs of stockings are summarized in table 3. The treatment had a great effect on some of the stockings and none on others.

TABLE 3.—*Results showing the effect of treating stockings with aluminum sulfate and soap.*

Designation of stocking	Endurability; cycles to failure[1]	Maximum load in first cycle	Distensibility; circumference at 30 pounds in first cycle	Elasticity; circumference at 30 pounds in first cycle minus circumference at 10 pounds in two-hundredth cycle
		Pounds	*Inches*	*Inch*
A, 2-thread, silk, untreated	205	75	17.4	[2]—1.9
A, 2-thread, silk, treated	1,000+	37	19.8	.9
B, 3-thread, silk, untreated	240	80	17.0	[2]—1.7
B, 3-thread, silk, treated	1,000+	51	18.6	.7
C, 4-thread, silk, untreated	346	113	16.3	[2]—1.3
C, 4-thread, silk, treated	1,000+	50	18.4	.6
D, 7-thread, silk, untreated	248	105	16.8	[2]—1.9
D, 7-thread, silk, treated	1,000+	68	17.7	.2
E, chiffon, silk, untreated	1,000+	60	17.7	—.1
E, chiffon, silk, treated	1,000+	62	17.6	.3
F, chiffon, silk, untreated	1,000+	63	17.7	—.2
F, chiffon, silk, treated	1,000+	62	17.8	.1
G, service, rayon, untreated	1,000+	77	17.7	[2]—1.0
G, service, rayon, treated	1,000+	83	17.5	[2]—.9
H, service, rayon, untreated	1,000+	80	17.3	[2]—1.3
H, service, rayon, treated	1,000+	82	17.3	[2]—1.3

[1] Tests were not continued beyond 1,000 cycles.
[2] These stockings appeared baggy after the test.

VI. EFFECT OF CONSTRUCTION

It is rather difficult to obtain stockings which are suitable for studying the effects of the various construction factors independently. In general, a change in the gage of the knitting machine is accompanied by a change in the number of courses per inch. A large change in the number of threads in the silk yarn necessitates a change in the gage of the knitting machine. Unless the stockings are especially knit for this purpose, varying only 1 factor at a time, and are then degummed, dyed, and finished alike, the effects of the various construction factors may be masked by the effects of degumming, dyeing and finishing.

However, the effects of these factors may be minimized and the general trend of the effects of the various construction factors found by a selection of results from those for the large series of stockings referred to in section III. These stockings were made to specified constructions by 13 manufacturers. Although the methods of degumming, dyeing, and finishing were not specified, the effects of variations in them probably would be relatively small when the endurability of the stockings is greater than 1,000 cycles. The following discussion is based upon the average results for stockings which did not fail in 1,000 cycles of test.

The curves in A of figure 8 indicate the effect which may be expected by varying the number of threads in the silk yarn. The stockings were knit on 42-gage knitting machines using 4- and 7-thread silk yarn. The 7-thread stockings were knit with an average of 41

courses per inch and the 4-thread stockings with an average of 43 courses per inch. The curves are based upon the average values obtained on stockings from 8 mills. As expected, the stockings knit from the 7-thread silk yarn require a greater load to distend to a given circumference than is required for the stockings knit from the 4-thread silk yarn. The effect due to the slight difference in the number of courses per inch, as will be shown below, would be to diminish the effect due to the difference in the number of threads. Thus the difference indicated may be considered as showing the true trend due to a difference in the thread.

The curves in B of figure 8 indicate the effect which may be expected by varying the number of courses per inch. The effect is shown for stockings knit from 4-thread silk yarn on 42- and on 45-

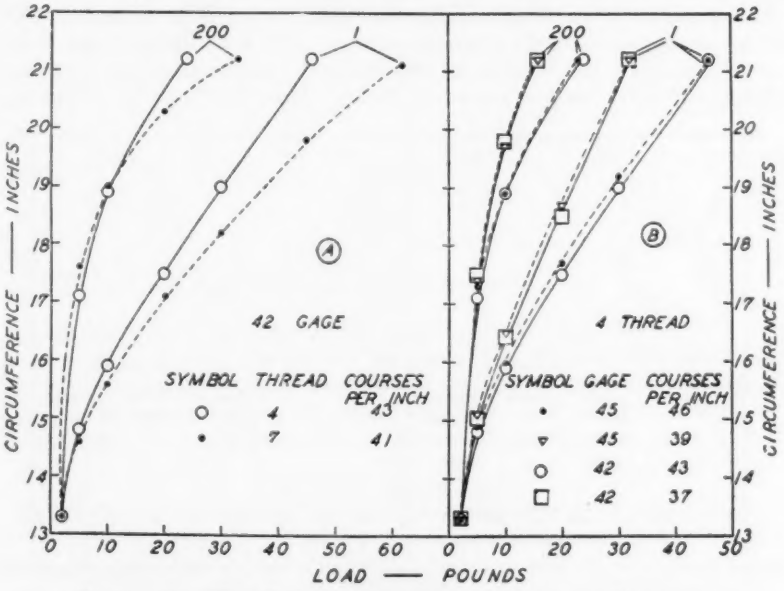

FIGURE 8.—*The effect of hosiery constructions on performance.*

The numbers on the curves indicate the loading cycle.

gage knitting machines. The curves show that a greater load is required to distend the stockings to a given circumference when the number of courses per inch is increased. This tendency is indicated by the stockings of both gages and is in agreement with that expected upon theoretical consideration. Take for example the 42-gage stockings with 37 and 43 courses per inch. The length of the silk yarn in 1 course in the stocking of 43 courses per inch is shorter than the length in 1 course in the stocking of 37 courses per inch. Obviously the stocking in which the length of yarn in 1 course is shorter and in which there are more courses per inch would require a greater load to distend to a given circumference.

The curves shown in B of figure 8 also indicate that the effect produced by increasing the gage from 42 to 45 is either small or is nullified by the difference in courses per inch. In view of the considerable effect noted above when the number of courses per inch is

changed, it appears that in the present case the effect due to a change in the gage is nullified by the difference in courses per inch. This is in agreement with what would be expected from theoretical consideration. In a 45-gage stocking there are approximately 7 percent more stitches or loops in 1 course or circumference than in a 42-gage stocking. If both stockings have the same number of courses per inch, then because of the greater number of loops in 1 course in the 45-gage stocking, the length of the silk yarn in 1 course, is approximately 7 percent greater than in a 42-gage stocking. On this basis a smaller load should be required to distend the 45-gage stocking to a given circumference.

VII. EFFECT OF KIND OF FIBER

The kind of fiber from which the yarn is made is a factor which will affect the behavior of the stockings. In A of figure 9 are shown curves obtained on 3 pairs of stockings of approximately the same weight. Two of the pairs are knit from 8-thread silk yarn. The third

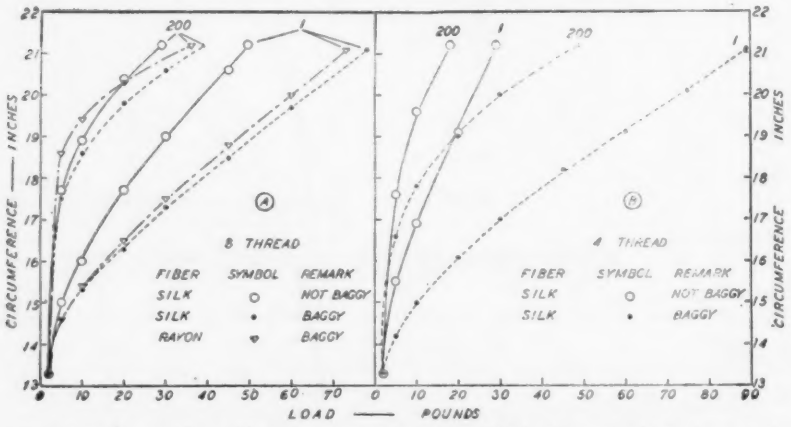

FIGURE 9.—*Curves for silk and rayon stockings which do and which do not show bagginess.*

The numbers on the curves indicate the loading cycle.

pair is knit from rayon yarn of about the same weight. The stockings were tested after laundering and all had endurabilities greater than 1,000 cycles. There is, however, a vast difference in the appearance of the tested stockings and their curves. The stockings made from rayon yarn are badly deformed or baggy. This is also true for 1 pair of the silk stockings, but not for the other. The similarity of the curves for the pair of silk stockings, which exhibited undesirable bagginess, and the curves for the rayon stockings and the great dissimilarity between the curves for the 2 pairs of silk stockings are very striking.

The curves obtained on 4 other pairs of rayon stockings as well as those obtained for the rayon stockings which are discussed in section V exhibited the same features as the curves shown for the rayon stockings in A of figure 9. This tendency of rayon stockings to become deformed or baggy with use is frequently considered to be an objectionable feature by the consumers. As is shown by these results and the

experience of consumers, this objectionable feature may also be encountered in some silk stockings.

The curves shown in A of figure 9 are for 2 pairs of 4-thread silk stockings obtained from 2 mills. The 1 pair showed no tendency to become baggy while the other pair showed a great tendency. Both pairs had endurabilities greater than 1,000 cycles.

TABLE 4.—*Results showing the relation of kind of fiber to extensibility and elasticity of stockings*

Thread	Fiber	Endurability; cycles to failure [1]	Maximum load of first cycle	Distensibility; circumference at 30 pounds in first cycle	Elasticity; circumference at 30 pounds in first cycle minus circumference at 10 pounds in two-hundredth cycle	Remarks
			Pounds	*Inches*	*Inch*	
8	Silk	1,000+	49	19.0	0.1	Not baggy.
8	do	1,000+	78	17.3	−1.3	Baggy.
8 [2]	Rayon	1,000+	73	17.5	−1.9	Do.
4	Silk	1,000+	29	21.2	1.6	Not baggy.
4	do	1,000+	89	17.0	−.8	Baggy.

[1] Tests were not continued beyond 1,000 cycles.
[2] The weight of the rayon yarn is equivalent to an 8-thread silk yarn.

These results, summarized in table 4, show that elasticity is definitely related to the tendency of stockings to become baggy. In general for stockings which show little tendency to become baggy, the elasticity is between 0 and 1 inch, whereas for stockings which show a great tendency it is between −1 and −2 inches.

VIII. SUMMARY

The principal results of this work are summarized in the following statements:

Laundering stockings before testing them on the machine may have a marked effect or no effect on the results of the test and the effect may be beneficial or detrimental. It appears that the effect of laundering depends largely upon the kind of finishing treatment the stockings have received.

The distensibility, elasticity, and endurability of degummed stockings were decreased by dyeing. Aging decreased the distensibility, elasticity, and endurability of both degummed and dyed stockings. This decrease was partially eliminated by laundering. Chemical tests indicate that the aging effect was not caused by a deterioration of the silk by exposure to light. It is probably attributable to a set of the yarns, which are plastic immediately after degumming, but become more rigid and therefore less free to bend and move one on another.

The "reversal effect" observed in the load-elongation diagrams of some stockings appears to be due to the kind of finish on the stockings. Laundering tends to eliminate this effect.

Marked differences in results were found to be produced by different commercial finishes on similar stockings. A finishing treatment of aluminum sulfate and soap was found to increase the distensibility, elasticity, and endurability of silk stockings which without the finish had endurabilities less than 350 cycles.

An increase in size of yarn or number of courses per inch in a stocking, or decrease in gage of the knitting machine on which a stocking is made, is accompanied by an increase in the load required to distend the stocking a given amount provided other factors remain constant.

The rayon stockings tested and some silk stockings become baggy on repeated distention. The tendency of stockings to become baggy is definitely related to the elasticity. In general a stocking with an endurability less than 1,000 cycles has less distensibility and elasticity than a stocking with an endurability greater than 1,000 cycles.

The hosiery-testing machine is suitable for measuring the differences in distensibility, elasticity, and endurability likely to occur in hosiery manufactured to be as nearly alike as practicable. The machine is suitable for researches on the effects of knitting, degumming, dyeing finishing, aging, laundering, redyeing, and refinishing of hosiery.

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U. S. Department of Commerce National Bureau of Standards

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FATIGUE PROPERTIES OF STEEL WIRE

By Stephen M. Shelton and William H. Swanger

ABSTRACT

Because of surface imperfections the fatigue limit of a structural member may be appreciably lower than the fatigue limit determined on machined and polished specimens of the material. This was shown by fatigue tests made by the rotating-beam method on galvanized heat-treated steel wire, Swedish valve-spring wire and cold-rolled mild steel wire: the fatigue limits of specimens with the original surfaces as produced by the manufacturers were 40, 60, and 82 percent, respectively, of the fatigue limits of machined and polished specimens of the same materials.

The development of a suitable gripping device made possible the determination of the limiting range of pulsating tensile stresses on unmachined (in the test length) specimens of wire in the Haigh alternating-stress testing machine.

The effect of variation of the mean stress between 50,000 and 200,000 lb/in.^{2} on the limiting ranges of pulsating tensile stresses was determined on cold-drawn and galvanized, and heat-treated and galvanized, steel suspension-bridge wires, and on a high-strength steel wire electroplated with zinc. The results showed that the limiting ranges of pulsating tensile stresses were practically independent of the mean stress within the range investigated.

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I. INTRODUCTION

For wrought metals, the tensile properties of test coupons are generally accepted as a criterion of the tensile properties of structural members. It has been found, however, that the fatigue limit of structural members is often less than that of machined and polished specimens of the same metal. As shown by many investigators, this is because the fatigue limit depends greatly upon the conditions at the surface, such as surface decarburization in steels, tool marks, notches, and some protective metallic coatings.[1 2 3 4]

[1] D. J. McAdam, Jr. and R. W. Clyne, *Influence of chemically and mechanically formed notches on fatigue of metals*, J. Research NBS. **13** (1934) RP527.

[2] G. A. Hankins and M. L. Becker, *The effect of surface conditions produced by heat treatment on fatigue resistance of spring steels*, J. Iron and Steel Inst. **124**, pt. 2, 387 (1931).

[3] R. H. D. Barklie and H. J. Davies, *The effect of surface conditions and electrodeposited metals on the resistance of materials to repeated stresses*, Proc. Inst. Mech. Engrs., p. 731, pt. 1 (1930).

[4] W. H. Swanger and R. D. France, *Effect of zinc coatings on the endurance properties of steel*, BS J. Research **9**, 9 (1932) RP454.

There are few testing machines in which fatigue tests can be made on full-size structural members. Fatigue tests can be made, however, on wire in the condition in which it is used in some structures, such as suspension-bridge cables. It is not necessary to machine the surface of the specimens. Several investigators have devised methods for holding the wire so that failure does not occur in the grips.

One of the authors of this paper devised a rotating-beam fatigue-testing method for wire. The results obtained on low-carbon steel wire and on high-carbon steel wire were reported in 1931.[5] The portion of this paper on "Rotating-Beam Tests" describes the method and gives results of additional tests.

F. C. Lea [6] used several methods for gripping wires in a torsional fatigue-testing machine. A. Lindeberg tested wire under pulsating tensile stresses. His machine is particularly adapted for testing small wires. The results of an extended series of fatigue tests on steel wires from 1 mm to 1.37 mm (approximately 0.04 in. to 0.054 in.) in diameter, made on his machine in collaboration with A. Pomp and C. A. Duckwitz, were reported in a paper by Pomp and Duckwitz.[7] Their tests were limited to determinations of the stress ranges which did not produce failure in 5,000,000 cycles of pulsating tension.

A. V. de Forest and L. W. Hopkins [8] used a modification of the rotating-beam fatigue-testing machine. The specimens were bent to a constant radius of curvature by wrapping them around a sheave for one-quarter of the circumference under a constant tension and rotating the wire. Their machine was used for testing small wire to be used in wire rope.

The results of fatigue tests of wires and small wire ropes, having lengths up to 50 feet, under combined tensile and bending stresses, were reported by R. L. Templin.[9] Recently E. T. Gill and R. Goodacre [10] described a rotating-beam machine for short specimens of wire.

In structures wire is usually subjected to stresses which fluctuate from one tensile value to another tensile value. In order to test wire under such fatigue stresses, tests were made in the Haigh alternating-stress testing machine. The portion of this paper on "Tests Under Pulsating Tensile Stresses" describes the method of testing in the Haigh machine and gives the results on different wires.

II. ROTATING-BEAM TESTS

The specimen for a rotating-beam machine is a round rod supported at the ends and loaded at 2 intermediate points. The specimen is rotated by a suitable driving mechanism. To avoid failures in the grips it is usual to machine the specimen to a reduced diameter at mid-length. A specimen having a constant cross section can be used if the specimen is so long that its weight provides sufficiently increased stresses at mid-length to cause failures at or close to that point. A machine designed on this principle is shown in figure 1. The specimens were wire having the cylindrical surface in the condition in which the wire is used. The supports, A and B, were taken from an

[5] S. M. Shelton, Proc. Am. Soc. Testing Materials, **31**, pt. 2, 204 (1931).
[6] Proc. Inst. Mech. Engrs. **120**, 661 (1931).
[7] Mitt. K. W. Inst. f. Eisenf. z. Düsseldorf **13**, 79 (1931).
[8] Proc. Am. Soc. Testing Materials, **32**, pt. 2, 398 (1932).
[9] Proc. Am. Soc. Testing Materials, **33**, pt. 2, 364 (1933).
[10] Preprint no. 3, Iron and Steel Inst. (Sept. 1934).

R. R. Moore rotating-beam fatigue-testing machine.[11] The specimen, C, is attached to the rotating spindles of the supports by means of a spring collet shown in figure 2. The loads, $W/2$, are suspended over quadrants, of lightweight metal, whose centers coincide with the centers about which the supports, A and B, are free to rotate. A constant moment is thus applied to the supports regardless of the deflection of the specimen. The support, A, is mounted on the frame so that it is free to move longitudinally. The base, E, for the motor, D, is mounted on hinges so that the shaft of the motor can be brought into approximate alinement with the spindle in support, B. A flexible coupling, F, joining the spindle and shaft, adjusts minor misalinement.

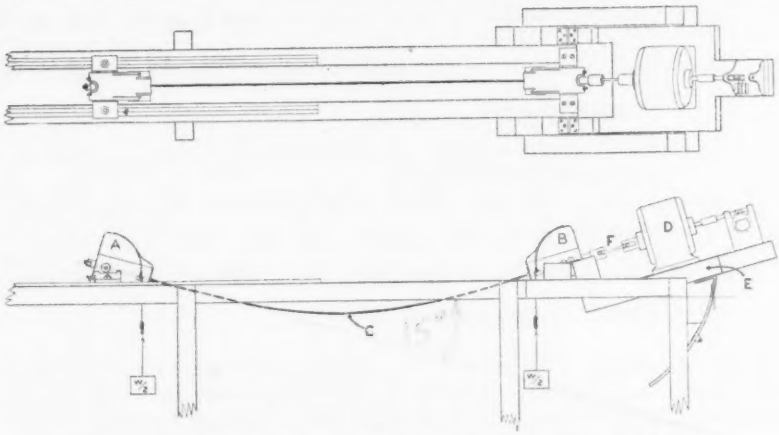

FIGURE 1.—*Long-span rotating-beam fatigue-testing machine.*

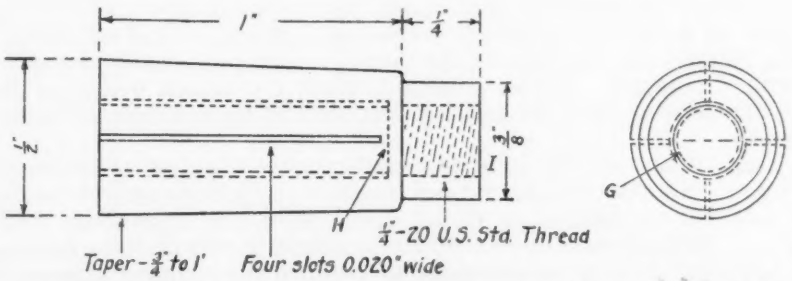

FIGURE 2.—*Gripping device for attaching specimens to bearing boxes of R. R. Moore machine.*

The specimen is inserted into the spring collet to the point, H (fig. 2). The collet is drawn into a tapered hole in the spindle of the support by means of a rod screwed into the collet at I, and anchored to the other end of the spindle. The specimen is gripped tightly by the tapered prongs of the collet as they are drawn into the spindle. The collet is lined with a bushing, G, to avoid seizing and galling on the surface of the specimen by the steel of the collet. Copper or several thicknesses of typewriter paper have been found suitable for this purpose.

[11] *Report of research committee on fatigue of metals*, appendix, Proc. Am. Soc. Testing Materials, **30**, pt. 1, 266 (1930).

The maximum fiber stress at the mid-length of the specimen can be computed from the formula:

$$S=\frac{(M_1+M_2)}{I/c}=\frac{W_1 l}{8}+\frac{W_2 a}{2}\div\frac{\pi}{32}d^3$$

where

S=maximum flexural stress, pounds per square inch.

M_1=bending moment (in inch-pounds) due to weight of specimen=$\frac{W_1 l}{8}$

W_1=total weight of specimen in pounds

l=horizontal distance from face of one grip to face of the other, in inches

M_2=bending moment (in inch-pounds) due to weights and supports=$\frac{W_2 a}{2}$

W_2=force due to weights+effective load due to weight of supports, in pounds

a=horizontal distance from bearing blocks to line of pull of weights, in inches

I/c=section modulus of specimen, for a circular specimen=$\frac{\pi}{32}d^3$

d=diameter of specimen in inches

If the specimen is in resonant vibration, the stresses are different from those calculated. Resonant vibration can be avoided in a specimen of a given length by changing the speed of rotation, or, for a given speed of rotation, by changing the length of the specimen. A few trials generally will show the proper length of specimen of wire of a given diameter that will run at a convenient speed of rotation (1,700 to 2,200 rpm) without excessive vibration. Final adjustment to eliminate all vibration is then easily made by a small change in speed of rotation. Hence a variable speed d-c motor to rotate the specimens was found to be more convenient than a constant-speed motor.

This method obviously is adaptable also to the fatigue testing of tubing. No attempts have been made to apply it to fatigue testing of soft iron or nonferrous metal wire. Wire less than about 0.125 inch in diameter cannot be used conveniently in this machine because of the large deflections necessary to produce the required stresses in the long span. In the Haigh-Robertson machine used by Gill and Goodacre,[12] an axial thrust is applied to the ends of a rotating wire so that the specimen becomes in effect an Euler strut. The mechanism is small, making operation at high speed (14,000 to 18,000 rpm) convenient, and can be used with wire 0.080 inch or less in diameter.

Fatigue tests were made with the long-span rotating-beam machine on 3 types of carbon-steel wire. Carbon and manganese contents and tensile properties are given in table 1. Material HG was a galvanized, oil-quenched and tempered, steel wire, 0.192 inch nominal diameter, manufactured for use in suspension-bridge cables; HGS was the same material with the zinc coating removed by solution in

[12] Preprint no. 3, Iron and Steel Inst. (September 1934).

Correction to page 20 of Research Paper RP754 of January 1935 Journal of Research of the National Bureau of Standards

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For the formula to compute the maximum fiber stress at the mid-length of the specimen, as given originally, substitute the following:

$$S = \frac{(M_1 + M_2)}{I/c} = \left(\frac{W_2 a}{2} + \frac{W_1 l}{8} + \frac{W_1 b}{2}\right) \div \frac{\pi}{32} d^3$$

b = horizontal distance from face of grip to point of support

TABLE 1.—*Materials and r*

Material	Carbon and manganese	Tensile pro	Stress for permanent ext in 8 inches, of—	
			0.002%	0.003%
	Percent		lb/in.²	lb/in.²
(HG) Heat-treated bridge wire, galvanized	0.75 C .50 Mn	1	82,000	100,000
(HGS) Heat-treated bridge wire, stripped of zinc coating	.75 C .50 Mn	1	82,000	100,000
(HG) Machined and polished	.75 C .50 Mn		60,000	63,000
(CR) Cold-rolled steel rod	.13 C			
(CR) Machined and polished	.13 C		104,000	119,000
(WC) Swedish valve-spring wire	.65 C .55 Mn			
(WC) Machined and polished	.65 C .55 Mn		102,000	117,000
(WO) Swedish valve-spring wire	.65 C .55 Mn	1		
(CD) Cold-drawn bridge wire, galvanized	.75 C .50 Mn		40,000	45,000
(CD) Machined and polished	.75 C .50 Mn			
(EG) Electrogalvanized wire	.71 C .97 Mn			

hydrochloric acid;[13] CR was commercial "cold-rolled steel" rod 0.187 inch in diameter; WC and WO were "oil-tempered" valve-spring wires of Swedish manufacture, 0.162 and 0.148 inch nominal diameter.

The speed of rotation was approximately 2,000 rpm for the galvanized bridge-wire specimens, HG, and 1,900 rpm for the stripped specimens, HGS; the cold-rolled steel specimens, CR, were run at 1,700 rpm. The length of span between the grips for these 3 types of specimens was 60 inches plus or minus 1 inch. The maximum fiber stress at the middle of the span, due to the weight of the wire between grips, was approximately 6,000 lb/in.^{2} The valve-spring wires were run at approximately 2,200 rpm. The length of span for the 0.162-inch diameter specimens, WC, was 46 inches plus or minus 1 inch. The maximum fiber stress at the middle of the span due to the weight of the wire was approximately 4,200 lb/in.^{2} for the larger and 3,600 lb/in.^{2} for the smaller wire.

The increased fiber stresses due to the weights of the wires were sufficient to cause more than 90 percent of the fractures to occur within 12 inches of the middle of the span. Fractures which occurred more than 12 inches from the mid-point were not included in the results reported. Variation in the stress over the lengths of the wire 12 inches on each side of the center was no greater than the variation due to possible errors in measurement of the diameters. For the galvanized specimens the stresses were computed on the diameter of the stripped wires.

Results for the bridge wire specimens are given in figure 3. The fatigue limit of the galvanized wire, HG, was 50,000 lb/in.^{2} The endurance ratio (fatigue limit to ultimate tensile strength) was only 22 percent. Specimens of the same material with the zinc coating removed had a fatigue limit of 60,000 lb/in.^{2}, an endurance ratio of 27 percent. These fatigue limits are unusually low for materials with an ultimate tensile strength of 225,000 lb/in.^{2} That the cause can be attributed to surface imperfections was shown by the results obtained on specimens machined from the wire. These were tested in the R. R. Moore rotating-beam fatigue-testing machine. The specimens, 3 inches long, were machined from the original diameter of 0.192 inch to a diameter of 0.150 inch in the midsection, with a radius of curvature at the reduced section of 9⅞ inches. The machined surface was polished longitudinally with 0000 emery paper. The specimens were held in collets similar to those shown in figure 2. The fatigue limit of the machined and polished specimens was 110,000 lb/in.^{2}, an endurance ratio of 49 percent. The *S–N* curve for these specimens is shown in figure 3.

The *S–N* curves for the cold-rolled steel, CR, are shown in figure 4. For the specimens tested with the original surface intact the fatigue limit was 46,000 lb/in.^{2}, an endurance ratio of 50 percent. For the machined and polished specimens of this material (reduced diameter of 0.150 inch) the fatigue limit was 56,000 lb/in.^{2}, an endurance ratio of 60 percent. The higher endurance ratios of this material in comparison with that of the stripped heat-treated bridge wire may have been due to the lesser notch sensitivity of the softer and more ductile

[13] The specimens were stripped of zinc by immersion in HCl (sp gr 1.19) to which had been added 1.6 g of $SbCl_3$ per liter of HCl: *Standard method of determining weight of coating on zinc-coated iron or steel articles*, ASTM Standards, A 90-33, pt. 1, 317 (1933).

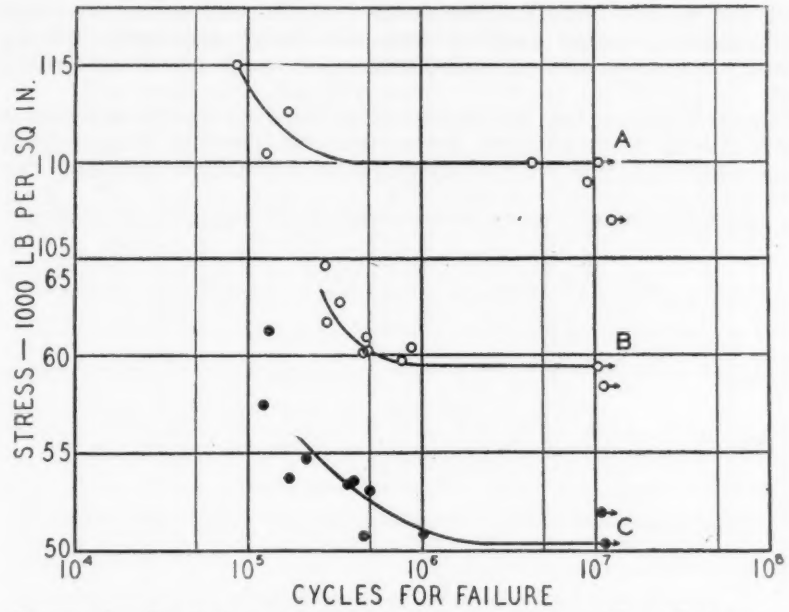

FIGURE 3.—*Results for rotating-beam fatigue tests on heat-treated bridge wire.*

Curve A, machined and polished specimens; curve B, specimens stripped of zinc; curve C, specimens of the galvanized wire.

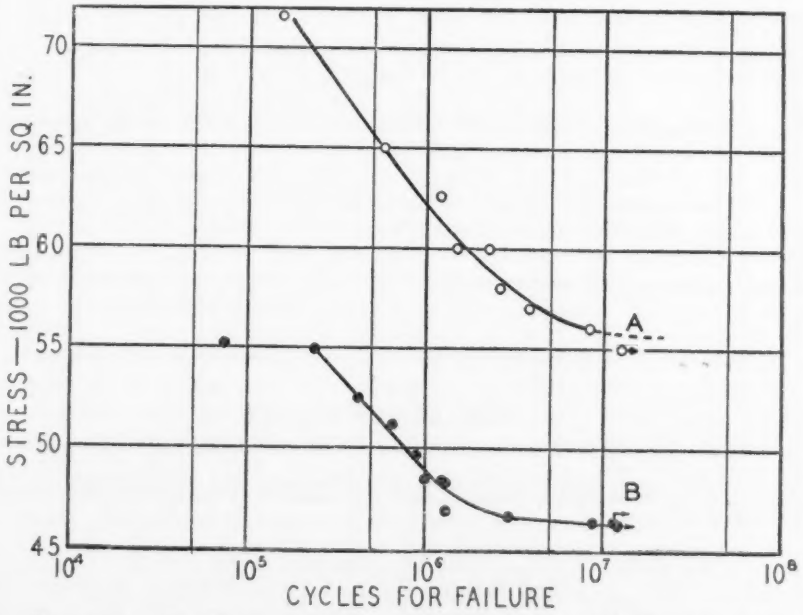

FIGURE 4.—*Results for rotating-beam fatigue tests on cold-rolled steel rods.*

Curve A, machined and polished specimens; curve B, specimens with original surface.

steel and to the fact that the surface of the cold-rolled steel was much more smoothly finished than the bridge wire and that the finishing operation formed work-hardened material on the cold-rolled steel.

The *S–N* curves for the valve-spring wires are shown in figure 5. Curve A was obtained from the results with short (3 inches) specimens machined to a reduced diameter of 0.130 inch from the WC

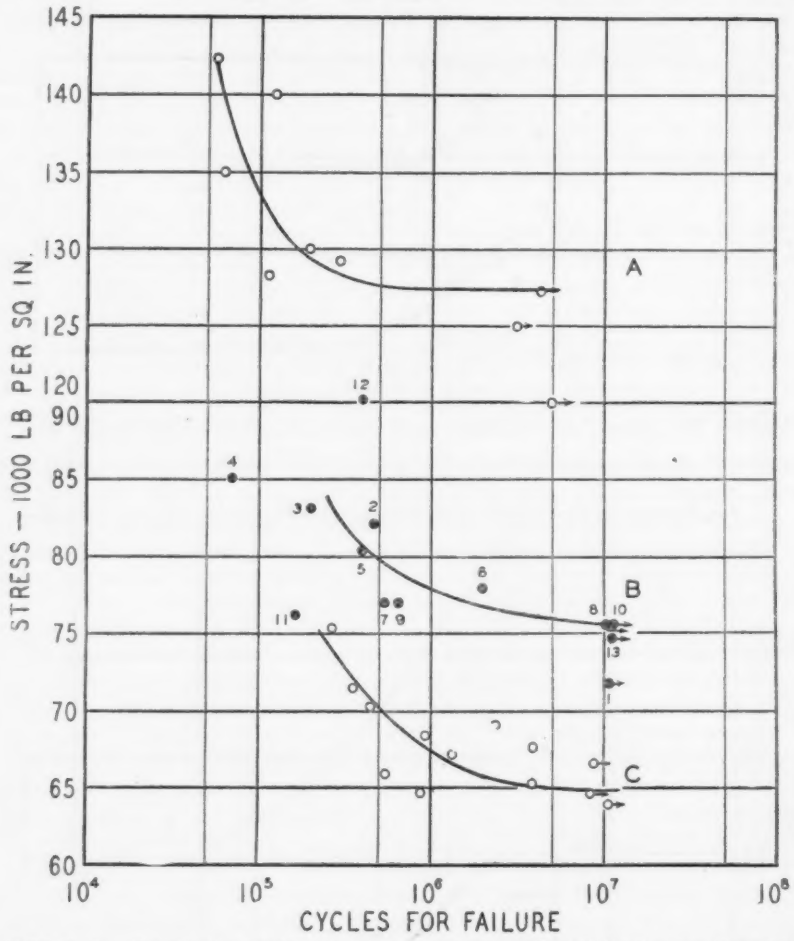

FIGURE 5.—*Results for rotating-beam fatigue tests on Swedish valve-spring wire.*

Curve A, machined and polished specimens of wire (WC, table 1) originally 0.162 in. in diameter; curve B specimens of wire WC, 0.162 in. in diameter; curve C, specimens of wire (WO, table 1) 0.148 in. in diameter, original surface retained.

wire, 0.162 inch original diameter, and tested in the R. R. Moore machine. The indicated fatigue limit of 126,000 lb/in.^{2} corresponds to an endurance ratio of 56 percent. For specimens with the original surface, tested in the long-span machine, a fatigue limit of only 76,000 lb/in.^{2} was obtained, an endurance ratio of 34 percent. It is noteworthy that in the latter group of tests, on each of the specimens that fractured at a number of cycles to the left of curve A, figure 5

(specimens 3, 4, 7, 9, and 11), the nucleus of fracture was located in a surface defect, a typical example of which is shown in figure 6 (A). One of the fractured surfaces of this specimen is shown in figure 6 (B). The nucleus of the fracture is indicated by the arrow. The appearance of the surface in the vicinity of the fractures typical of specimens 2, 5, 6, and 12, is shown in figure 6 (C). Figure 6 (D) shows the appearance of the fractured surface of one of these specimens. There is no indication of a surface defect in the nucleus of the fatigue fracture. Figure 6 (E) shows the appearance of the surface on the machined and polished specimens of this material, for which a fatigue limit of 126,000 lb/in.^{2} was indicated.

For the valve-spring wire, WO, 0.148 inch in diameter, a fatigue limit of 65,000 lb/in.^{2} was obtained on unmachined specimens tested in the long-span machine. The endurance ratio was only 30 percent. This wire was too small to permit tests of machined and polished specimens with the equipment available.

The *S–N* curve, C, figure 5, shows that there was less "scatter" in the results obtained with this wire than with the 0.162-inch diameter wire, WC. A reason for this was indicated by the examination of the surfaces of the fractured specimens adjacent to the fractures. No unusual surface defects at the nuclei of fracture were found; the surfaces of all the specimens were similar to that shown in figure 6 (C).

III. TESTS UNDER PULSATING TENSILE STRESSES

Fatigue tests under pulsating tensile stresses in the Haigh machine were made on materials HG and WO, listed in table 1, and also on 2 additional materials for which carbon and manganese contents and tensile properties are given in the table. Material CD was a suspension-bridge cable wire manufactured by cold-drawing ⅜-inch hot-rolled and "patented" rods through 5 passes to 0.192-inch nominal diameter. The drawn wire was galvanized by the hot-dip process, the coating being approximately 0.002 inch thick. Material EG was a cold-drawn wire coated with zinc by a commercial electrodeposition process. The thickness of the coating was 0.0035 inch.

The Haigh fatigue-testing machine permits a pulsating stress to be superimposed on an initial tensile stress on the specimens. The initial tension was applied to the specimen through a spring, the tension of which was regulated by a graduated nut. The graduations on the nut were calibrated by means of a specimen of the same wire as that used for the fatigue tests. The extensions of the calibration specimen, produced by known loads in a tensile-testing machine, were measured with a Ewing extensometer. The calibration specimen was then transferred to the Haigh machine and tension was applied by turning the nut. The resulting extensions measured with the same extensometer, were a direct measure of the tensile loads produced by turning the nut to the various graduated marks.

The upper end of the specimen for the fatigue test was attached to the fixed head on the machine and the lower end was attached to an armature which oscillated between the pole pieces of 2 electromagnets alternately excited by a 2-cycle generator. The maximum tensile stress is the sum of the initial stress imposed by the spring (attached to the armature) and half the range of pulsating stress imposed by the magnets. The minimum tensile stress is the initial

stress minus half the range of pulsating stress. Equality of the increments of pulsating stress above and below the initial stress was maintained by means of a handwheel provided on the machine, which moved the specimen and armature, up or down, so that the armature attached to the lower end of the specimen was midway between the pole pieces. The midway point was indicated by a zero reading of a differential ammeter showing that the currents in both magnet circuits were equal. When this condition was maintained the initial stress set up in the specimen was the mean of the pulsating stresses.

The magnitude of the ranges of pulsating stresses used with different values of mean stress was indicated on a "stress meter" actuated by the magnets. The readings of the stress meter were also calibrated in terms of the load-extension relations of the calibration specimen of each type of wire.

During the tests at the higher values of mean stress the specimens acquired a permanent extension which disturbed the equality of oscillation of the armature about the midpoint between the pole pieces and lowered the initial stress imposed by the spring. It was necessary to readjust the load on each specimen at the beginning of a test because of the extension of the specimen and because of a small amount of yielding in the grips as they gradually seated themselves more firmly on the specimens. This readjustment by means of the handwheel was generally completed during the first 50,000 stress cycles, after which all the specimens appeared to assume a uniformly cylic state with no further permanent extension for the duration of the test.

It was found by measurement of the diameters of a number of permanently stretched specimens that the increase in stress due to the reduced diameter was well within the experimental error of the stress determinations, which is believed to be less than 5 percent. Accordingly, the stresses recorded in the test results are those calculated on the original diameters of the specimens and the limiting ranges given for the higher values of mean stress are on the "safe" side.

The 3 types of zinc-coated wires differed in thickness of coating. Hence, in order to have a more nearly common basis for comparison, the stress calculations were based on the diameters of the stripped wires.

With no reduced diameter in the portion of the test specimen between the grips, unavoidable clamping stresses would cause most of the fractures to occur within the grips. It was found that by grinding the zinc off the ends and polishing the exposed steel surface of the galvanized wires, or polishing the original surface of the ungalvanized wires, as far as they extended into the grips, the endurance strength of that portion of the specimen was increased sufficiently over the endurance strength of the portion between the grips so that fractures within the grips were avoided. The galvanized specimens were reduced in diameter as much as 0.008 inch in the gripped portions. The clamping stresses were distributed as uniformly as possible by the gripping device, a cross section of which is shown in figure 7.

A threaded fitting, A, was used to make the attachment to the machine, and as a seat for the tapered plug, C, which is essentially a spring collet. The hole in the collet through which the specimen, S, extended was drilled with a twist drill, and 4 radial slots were cut 90° apart to within about one-fourth inch from the smaller end.

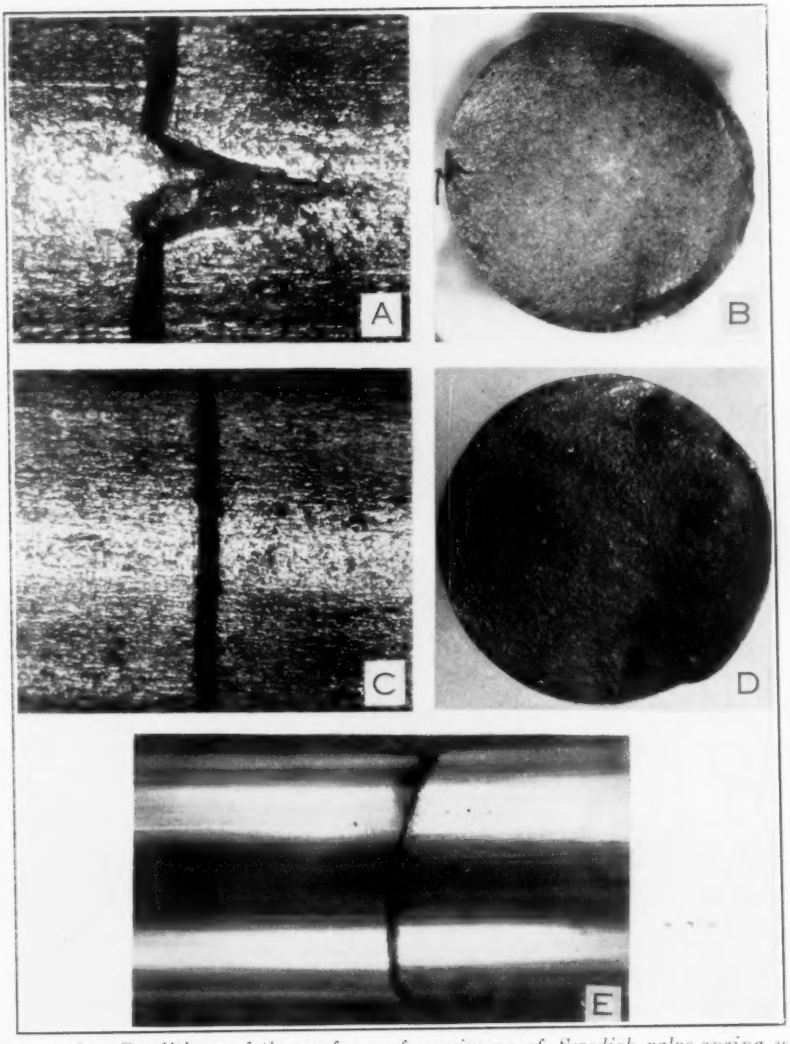

FIGURE 6.—*Conditions of the surfaces of specimens of Swedish valve-spring wire* WC, *table 1.*

A, Surface defect, specimen no. 4, from curve B, figure 5, X50. B, Surface of fracture of specimen no. 4; nucleus of fracture, indicated by arrow, located at surface defect shown in A, X16. C, Typical appearance of surface close to fractures which did not originate in major defects, X50. D, Appearance of fracture of specimen with no visible surface defect in nucleus of fatigue fracture, X16. E, Appearance of surface of machined and polished specimens, X16.

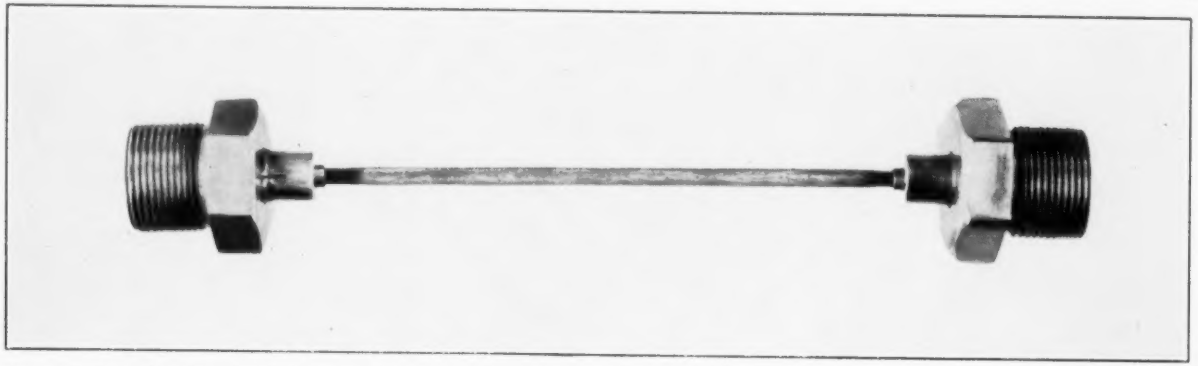

FIGURE 8.—*A galvanized-wire fatigue-test specimen with gripping device attached, as used in Haigh machine, ½ size.*

Parts A and C were made from machinery steel. A heat-treated steel nut, N, threaded on about one-half inch of the end of the specimen was seated on the larger end of the collet. A pull exerted on the specimen drew the collet through the tapered hole in the threaded fitting, A, and caused the collet to grip the polished end of the specimen. The specimen was thus held partly by the nut and partly by friction between the collet and the specimen. A soft metal bushing, B, slipped over the end of the specimen, aided in distributing uniformly the stresses caused by the pressure of the collet. Copper and brass tubing were tried, but proved to be unsatisfactory because both galled the steel surface of the specimen and frequently fatigue fractures radiated from the galled areas. This difficulty was practically eliminated with a bushing drilled from a rod of copper-lead bearing alloy containing approximately 25 percent lead, or by wrapping the ends of the specimens with several layers of typewriter paper.[14]

Figure 8 shows a specimen mounted in the grips. The length of the specimens was 10 inches. The machine operated at a rate of 2,400 cycles per minute.

Results of the determinations of the limiting range of pulsating tensile stress for the 4 types of wire at a mean tensile stress of approximately 110,000 lb/in.^{2} are shown in figures 9 to 12. Both the maximum and minimum stresses are plotted to show a clearer picture of the stress conditions than if only the semirange of stress were shown, as is usual for completely reversed stresses. Determinations were made at only one mean stress for the valve-spring wire.

The limiting ranges of pulsating tensile stress, determined in the same way, at 6 different mean stresses, are shown in figure 13 for the heat-treated galvanized bridge wire and in figure 14 for the cold-drawn galvanized bridge wire.

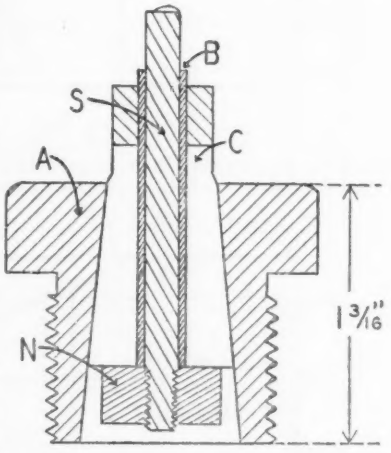

FIGURE 7.—*Gripping device for attaching specimens of wire to Haigh alternating-stress testing machine.*

The fatigue limits for complete reversal of stress, as determined by the rotating-beam method on the galvanized heat-treated bridge wire and on polished specimens machined from the wire, are also shown in figure 13. It was not possible to make rotating-beam tests on the cold-drawn galvanized bridge wire and on the electrogalvanized wire on the long-span machine because of the curvature of the wires, imparted in drawing as they were coiled on the take-up blocks. The rotating-beam fatigue limit obtained on short polished specimens machined from the cold-drawn bridge wire is shown in figure 14. In this figure are plotted also the maximum and minimum stresses of the limiting ranges of pulsating tensile stresses determined at 5 mean stresses for the electrogalvanized wire (EG, table 1.) Curves connecting the plotted points were not drawn, but it is evident that they would be practically parallel to those for the galvanized bridge wires.

[14] A much more elaborate method for gripping wire specimens for tests in the Haigh machine was described by R. Goodacre in Engineering, **137,** 503 (1934).

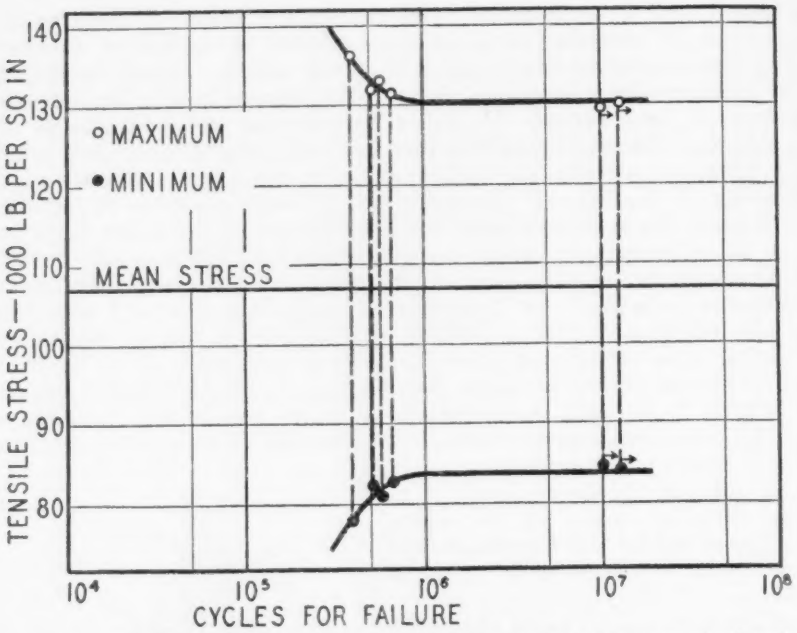

FIGURE 9.—*Results for pulsating tensile-stress fatigue tests on heat-treated galvanized bridge wire at a mean stress of 107,000 lb/in.²*

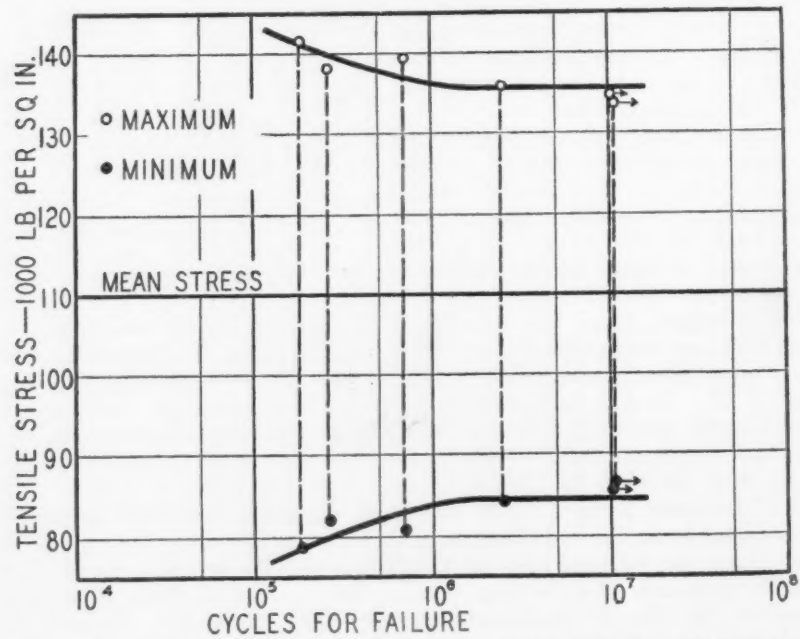

FIGURE 10.—*Results for pulsating tensile-stress fatigue tests on cold-drawn galvanized bridge wire at a mean stress of 110,000 lb/in.²*

It was not practicable to make determinations of the limiting ranges of tensile stress on the galvanized wires at mean stresses much below the lowest value used, because it is necessary to maintain a minimum stress of about 10,000 lb/in.^{2} to keep the wire straight. The capacity of the machine did not permit tests to be made on these wires at mean stresses higher than those used.

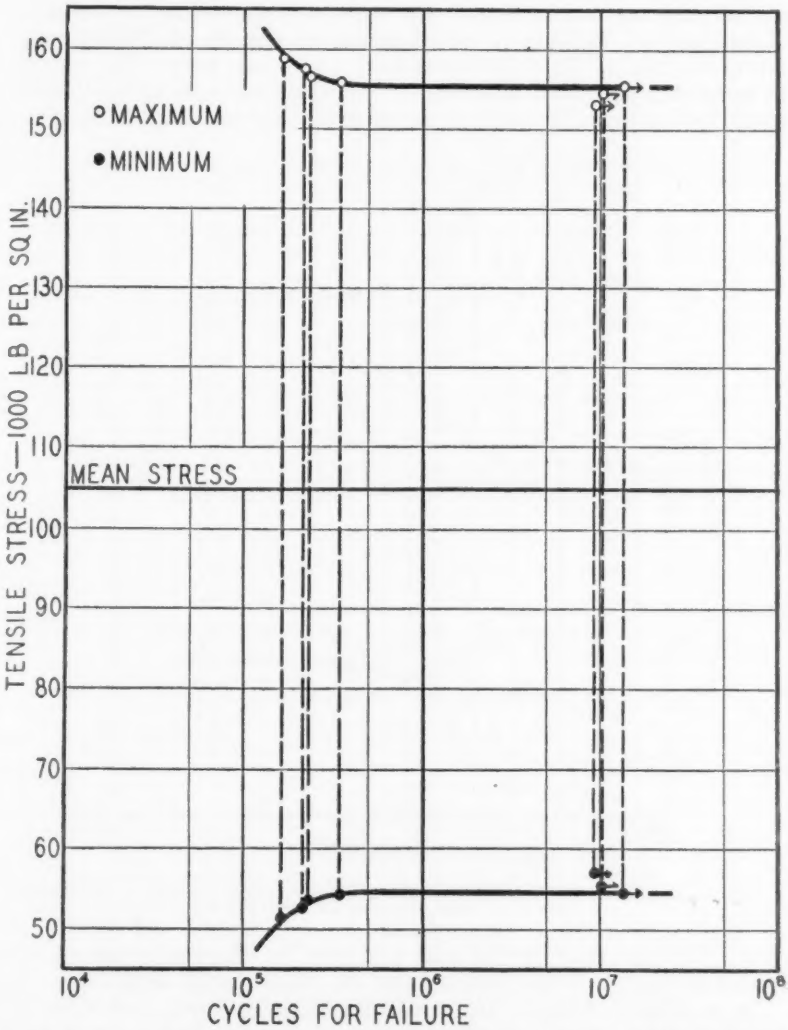

FIGURE 11.—*Results for pulsating tensile-stress fatigue tests on Swedish valve-spring wire at a mean stress of 105,000 lb/in.*^{2}

For the 3 types of galvanized wire the limiting range of pulsating tensile stress was slightly greater at the lowest mean stress, 50,000 lb/in.^{2}, than at any of the higher mean stresses employed and was practically the same for all the mean stresses above 50,000 lb/in.^{2} For the Swedish valve-spring wire the limiting range of pulsating tensile stress was about twice as great as those obtained on the 3

zinc-coated wires at approximately the same mean stress. By the rotating-beam tests the fatigue limit of this valve-spring wire was 30 percent higher than that obtained on the heat-treated galvanized bridge wire.

IV. SUMMARY

Two methods were devised for fatigue testing of steel wire without altering the original surface of the wire in preparation for the tests.

One method utilized a modification of the R. R. Moore fatigue-testing machine. The specimens were 4 to 6 feet long. The weight of the specimen provided sufficiently increased stresses at midlength to cause the fractures to occur at or close to that point instead of in the

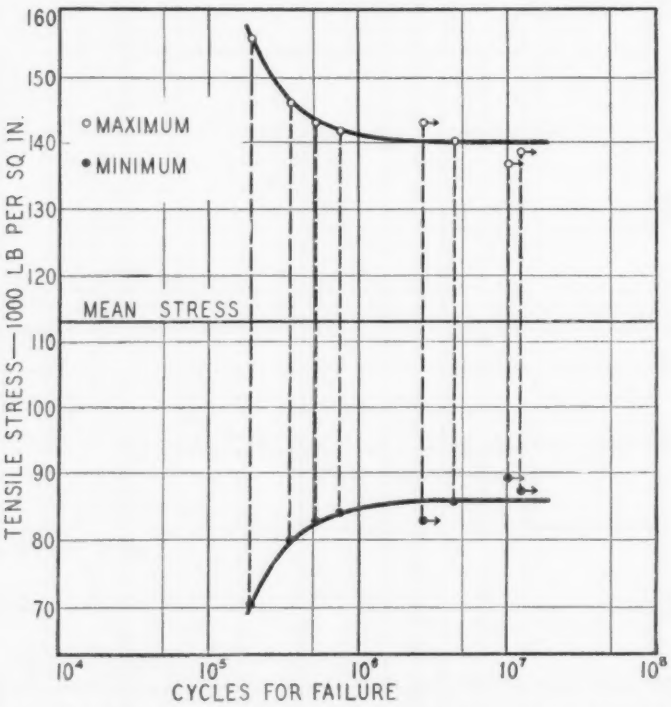

FIGURE 12.—*Results for pulsating tensile-stress fatigue tests on electrogalvanized wire at a mean stress of 113,000 lb/in.*^{2}

grips. The gripping device was designed to distribute the clamping stresses as uniformly as possible over the gripped ends of the specimens.

The fatigue limits of a heat-treated and galvanized steel wire, 0.192 inch diameter, a Swedish valve-spring wire 0.162 inch diameter, and a cold-rolled mild steel wire 0.187 inch diameter were 45, 60, and 82 percent, respectively, of the fatigue limits obtained on short (3-inch length) machined and polished specimens of the same materials, with the diameters of the 2 larger wires reduced to 0.150 inch and that of the smallest to 0.130 inch.

With the use of a suitable gripping device it was found possible to make fatigue tests in the Haigh alternating-stress testing machine on specimens of wire with the original surface unaltered in the test

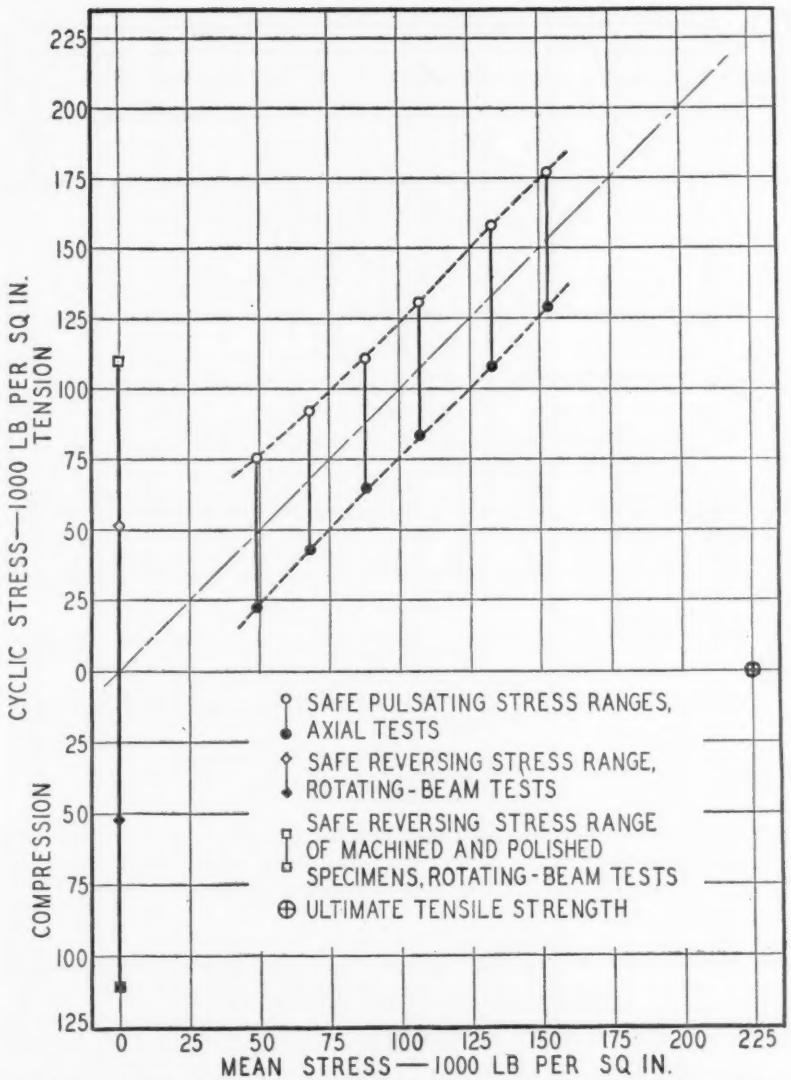

FIGURE 13.—*Relation between mean stress and limiting ranges of pulsating tensile stress.*

Heat-treated galvanized bridge wire

length. The limiting ranges of pulsating tensile stresses were determined at various mean stresses between 50,000 and 200,000 lb/in.^{2} on cold-drawn and galvanized, and heat-treated and galvanized, steel bridge wires, and on a high-strength steel wire electroplated with zinc.

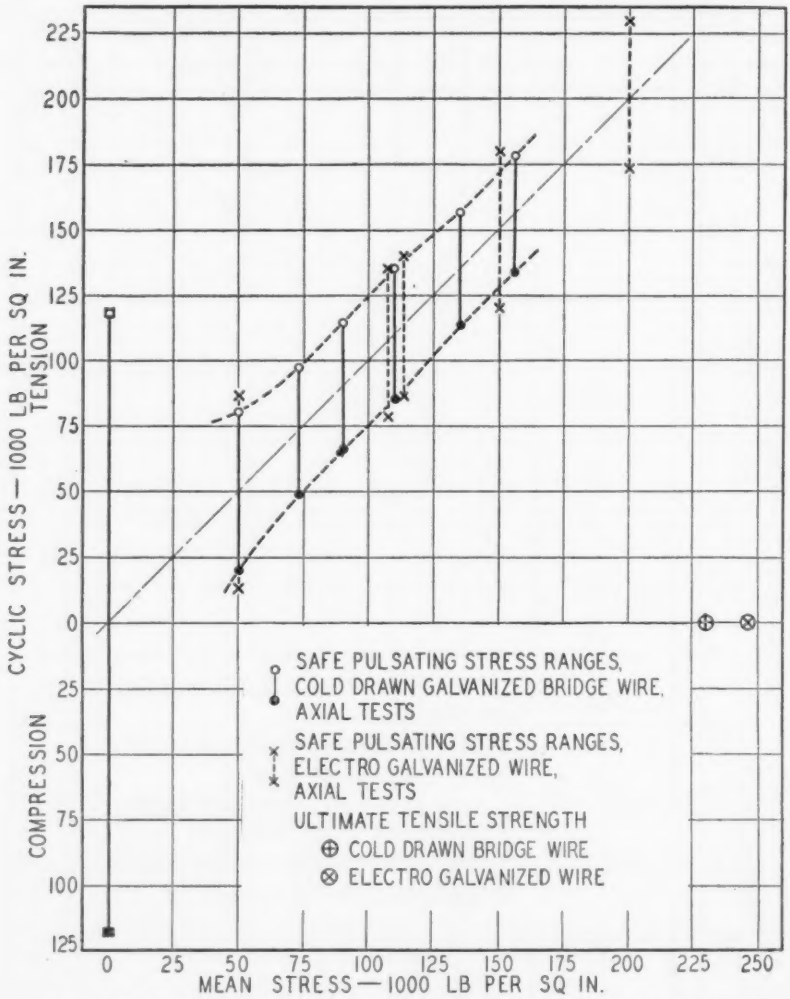

FIGURE 14.—*Relation between mean stress and limiting ranges of pulsating tensile stress.*

Cold-drawn galvanized bridge wire and electrogalvanized wire. Points on zero ordinate show safe reversing stress range of machined and polished specimens of cold-drawn bridge wire according to rotating-beam tests.

The results showed that the limiting ranges of pulsating tensile stresses were practically independent of the mean stress within the range investigated.

WASHINGTON, November 28, 1934.

U. S. Department of Commerce National Bureau of Standards

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INTERFERENCE MEASUREMENTS IN THE INFRARED ARC SPECTRUM OF IRON

By William F. Meggers

ABSTRACT

Wave lengths of the stronger infrared radiations characteristic of integrated light from an iron arc at atmospheric pressure are measured relatively to neon standards by the Fabry-Perot interferometer method. Values are given for 91 lines ranging from 7164.469 to 10216.351 A. Spectral term combinations indicate that most of these lines require relatively high excitation energies, which accounts for their character and properties. Differences between values from integrated arc light at atmospheric pressure and from the vacuum arc are interpreted as pressure- and Stark-effects. It is suggested that the international system of secondary standards of wave length can be extended into the infrared by using integrated light from an iron arc at 1 atm pressure.

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I. INTRODUCTION

The iron arc at atmospheric pressure has served for many years as a source of secondary standards for wave-length measurements in optical spectra. Selected lines in the atomic spectrum of iron first attained the status of international secondary standards through the action of the International Union for Cooperation in Solar Research [1] in 1907, and were continued as such, after the war, by the International Astronomical Union. In 1928 the values were revised on the basis of new observations and 319 lines ranging from 3370.787 to 6750.156 A were adopted as iron arc secondary standards of wave length.[2] Provisional values for iron lines which may serve as standards among shorter waves to 2015 A have been proposed [3] but require confirmation before they can be adopted as international standards.

The first interference measurements of iron lines in the region of longer waves (to 8824 A) were made by Burns [4] in 1913. Similar results were reported by Meggers and Kiess [5] in 1924, since which

[1] Trans. I. U. S. R. **4,** 58 (1914).
[2] Trans. I. A. U. **3,** 86 (1928).
[3] Trans. I. A. U. **4,** 71, 74 (1932).
[4] K. Burns, Jour. de Phys. [5], **3,** 457 (1913).
[5] BS Sci. Pap. **19,** 273 (1924).

time no further interference observations appear to have been made on infrared iron lines. In recent years, the discovery of new dyes which impart infrared sensitivity to photographic emulsions has greatly extended the range of precision measurements in spectroscopy, and immediately created a need for standards in this range. After a preliminary description of the iron-arc spectrum extending to 10863 A had been obtained [6] it appeared desirable to refine the infrared measurements by means of interference observations and thus investigate further the practical utility of the iron arc as a source of secondary standards. This paper reports on interference measurements of 91 lines, with corresponding wave lengths ranging from 7164 to 10216 A, characteristic of integrated light from an arc, at atmospheric pressure, between 2 electrodes of iron.

II. APPARATUS AND METHODS

The apparatus and method devised by Fabry and Perot [7] for wavelength comparisons are too well known to justify detailed presentation here. A recent paper by Humphreys [8] gives an outline of the theory and describes a procedure in observing and measuring which was followed almost without variation in the present work. It is important, however, to give all essential facts about the light sources since it is now recognized that wave lengths derived from any source depend more or less on the exact specifications.

It may be recalled that the earliest interference measurements of iron lines were made before the importance of operating conditions was realized, and it was not until 1913 that the iron arc in air as a source of international standards was meticulously described [9] as follows: Length of arc, 6 mm; current of 6 amp for wave length greater than 4000 A, 4 amp or less for wave lengths shorter than 4000 A; direct current with positive pole above the negative, potential of 220 v; iron rods of 7 mm diameter for electrodes; axial part about 2 mm wide in center of arc to be used as a source of light; only lines of groups *a*, *b*, *c*, *d*, (Gale and Adams pressure groups) to be used as standards. Soon after these specifications were laid down, it was shown that certain iron lines exhibit a so-called "pole effect" represented by a change in wave length when light from the vicinity of an electrode is compared with that from the center of the arc, and the International Astronomical Union was persuaded [10] as follows with respect to the iron arc:

"In order to obtain lines of constant wave length, constant intensity distribution, and adapted to high orders of interference, the adoption is recommended of the Pfund arc [11] operated between 110 and 250 v., with 5 amp. or less, at a length of 12 to 15 mm used over a central zone not to exceed 1 to 1.5 mm in width, and with an iron rod 6 to 7 mm diameter as the upper pole and a bead of oxide of iron as the lower pole." At the same time it was recommended [12] that the arc previously described be retained as a source for waves longer than 6000 A, since

[6] W. F. Meggers and C. C. Kiess. BS J. Research, **9**, 309 (1932).
[7] Ann. chim. phys. [7], **25**, 98 (1902).
[8] BS J. Research **5**, 1041 (1930).
[9] Trans. I. U. S. R. **4**, 58 (1914).
[10] Trans. I. A. U. **1**, 36 (1922).
[11] Astrophys. J. **27**, 297 (1908).
[12] Trans. I. A. U. **1**, 36 (1922).

"the secondary standards to the red of λ6000 are all stable lines, and the exposures with the above-mentioned (long) arc may be rather long".

In view of the recent improvements in the sensitization of photographic emulsions to infrared light, I attempted in the present work to use the modified iron arc so that the long waves would be measured in the same source as the shorter ones. Unfortunately this was found to be entirely impractical even in the near infrared up to 8824 A which had previously been examined with the earlier (short) type of arc. The explanation is, no doubt, related to the fact that most of the infrared iron lines involve rather highly excited states and are, therefore, strongly developed only near the electrodes. Even the short arc (6 mm) was found to be impractical for interference observations beyond 9000 A when light was taken only from the central zone (2 mm) so that the apparatus was finally arranged in such a way that light from the entire arc, including that from the electrodes, was integrated in the interferometer. With this arrangement, it was found possible to record interference patterns for all of the stronger lines of iron up to wave length 10216 A with exposures of 1 to 2 hr on Eastman xenocyanine plates. The actual arrangement was as follows: The arc was placed at the principal focus of a collecting lens which then illuminated the interferometer with essentially parallel light. After passing through the interferometer the light was collected by an achromatic lens which projected, on the spectrograph slit, interference patterns of the individual radiations and also an image of the arc slightly magnified. By maintaining an electrode gap of about 12 mm in the arc, the electrode images on the slit were separated about 15 mm so that 5 or 6 rings of the interference patterns appeared between the continuous spectra from the electrodes. The arc was operated with a current of 8 amp, the applied potential being 240 v. The iron arc at atmospheric pressure consists of 2 flames coming from the electrodes, and Fabry and Buisson [13] have shown that the negative flame is much more brilliant than the positive, the difference being greatest for long waves. On account of this intensity difference it was necessary to alternate polarity during the exposure in order to obtain symmetrical illumination of the interference patterns. The exposures ranged from 5 to 10 min for the interval 7000 to 9500 A which was recorded on Eastman 144 RP plates, and 1 to 2 hr to photograph 8300 to 10800 A on Eastman 144 Q plates.

Instead of using the red radiation from cadmium as a primary standard for these wave-length comparisons it was found more convenient to utilize the yellow and orange lines of neon as emitted by a Geissler tube operated with a high-voltage transformer. Since it has been recognized that the mean of any 8 or more neon lines which have already been adopted as secondary standards is practically equivalent to the primary standard,[14] I have compared the infrared iron lines with such a group standard by determining the étalon thickness for each spectrogram from the best exposed neon lines between 5852 and 6304 A. The values actually used for this purpose were the 8-place means published by Jackson.[15] The neon exposures were made simultaneously with the iron by inserting between the arc collecting lens and the interferometer, a sheet of red (selenium) glass

[13] Jour. de. Phys. **9**, 229 (1910).
[14] Trans. I. A. U. **2**, 41 (1925).
[15] Proc. Royal Soc. A, **143**, 219 (1933).

transmitting arc light only of wave length >6400 A and reflecting neon light from its rear surface to illuminate the interferometer and spectrograph in like manner as the iron arc. A second collecting lens inserted between the neon lamp and the red glass filled the interferometer with parallel light and the capillary source was imaged on the slit simultaneously with the arc image. Thus the 2 overlapping settings of the spectrograph camera referred to above covered the entire range of infrared iron spectrum which could be photographed and each iron spectrogram was accompanied by a neon spectrogram (Eastman 144 F plate) representing the primary standard. In the first setting the neon spectrum was recorded in the grating's first order on the short-wave side of the iron, while in the second setting the neon was taken from the grating's second order on the long-wave side of the iron. This procedure brought both spectra near the axis of the grating and had the additional advantage of equalizing the exposures since the longer exposures for iron in the second range were fairly compensated by the lower brightness of the grating's second order spectrum. The grating spectrograph referred to here is the stigmatically mounted concave grating described in another paper.[16]

The interferometer consisted of silvered quartz plates of 6 cm aperture separated by invar étalons of 6.2, 10, or 15 mm length. Most of the measurements were made on spectrograms resulting from use of the 10 mm étalon, since the general character of many of the infrared lines of iron is such as to preclude orders of interference exceeding about 40000. The actual orders of interference for each line and each spectrogram were derived from measurements of the diameters of the first four rings in the interference patterns. When the first ring was estimated to yield a fractional order of 0.2 or less the fifth ring was measured instead.

Since the interferometer plates and silver films were the identical ones just previously used for interference measurements in the spectra of noble gases,[17] the last corrections for dispersion of phase at reflection determined in that work were applied to the present results for the spectrum of iron. For the 10 mm étalon this correction increased from −0.001 A at 7200 A to −0.004 A at 10000 A. The air temperature and barometric pressure were recorded for each exposure, but it was found that the corrections required to convert the wave lengths to standard atmospheric conditions (15° C, 760 mm) were usually less than 0.0005 A.

III. RESULTS

The results of my interference measurements of infrared wave lengths characteristic of integrated light from the iron arc at atmospheric pressure are presented in table 1. Column 1 contains the estimated relative intensities and the temperature classes as published by King.[18] In the next are presented the wave lengths in air at 15° C and 760 mm Hg pressure, the values being based upon neon standards. The third column shows the number of spectrograms on which each line was measured, each observation representing the average of measurements on 4 rings; the fourth column gives notes on the probable error of the arithmetical mean (column 2), the letters having sig-

[16] BS Sci. Pap. **18**, 191 (1922).
[17] W. F. Meggers and C. J. Humphreys, BS J. Research **13**, 293 (1934).
[18] A. S. King, Astrophys. J. **80**, 124 (1934).

nificance as follows: "*A*" indicates a probable error less than 0.0007 A, "*B*" 0.0007 to 0.0012 A, and "*C*" a still larger probable error. When the probable error exceeds 0.004 A the value entered in column 2 is limited to 2 decimal places. It may be pointed out that a given probable error expressed in Angstrom units is only half the percentage error for 10000 A that it is for 5000 A. This column also contains for certain lines a letter "*h*", which means that the interference patterns appear hazy or diffuse as compared with the remaining lines. The fifth column is derived from the second with the aid of Kayser's Tabelle der Schwingungszahlen, while the sixth and seventh represent data quoted from the paper on "Wave Lengths and Atomic Levels in the Spectrum of the Vacuum Iron Arc by Burns and Walters."[19] It is sufficient to quote only the value of the lower term, since the higher one can be derived from the former by adding the wave number of the line represented (column 5), the fractional part of this wave number being taken from column 8, to obtain the vacuum-arc value of the higher excited state. In the last column differences between the vacuum arc and the atmospheric arc are shown both in Angstrom units and in wave numbers. These differences have practical value in that they enable one to transform values from either source to the other, and they are of considerable theoretical interest in any discussion of their probable origin.

TABLE 1.—*Interference measurements in the infrared arc spectrum of iron*

Intensity and temperature class [a]	λ Integrated light of arc in air	Number of observations	Character of line and probable error	Wave-number in vacuum	Term combination [b]	Value of lower term [b]	Wave-number arc in vacuum		Difference vacuum arc—air arc	
							Observed	Computed	λA	ν cm⁻¹
250 V	7164.469	6	*A*	13953.929	$b^5D_2^2$—b^5F^3	33801.608	.970	.963	−.017	+.034
800 V	7187.341	7	*B*	13909.525	$b^5D_4^4$—b^5F_5	33095.976	.569	.562	−.019	+.037
500 V	7207.406	7	*B*	13870.801	$b^5D_3^3$—b^5F_4	33507.161	.836	.830	−.015	+.029
80 V	7389.425	6	*B*	13529.132	$b^5F_1^1$—b^5F^1	34692.177		.175	−.024	+.043
4 IV	7401.689	3	*A*	13506.715						
100 V	7411.178	7	*B*	13489.422	$b^5F_2^1$—b^5F^2	34547.243	.458	.459	−.020	+.037
5 IV	7418.674	3	*A*	13475.792						
200 V	7445.776	8	*B*	13426.742	$b^5F_3^2$—b^5F_3	34328.787	.783	.784	−.023	+.042
400 V	7495.088	6	*A*	13338.404	$b^5F_4^3$—b^5F^4	34039.548	.440	.443	−.022	+.039
800 V	7511.045	5	*C*	13310.067	$b^5F_5^4$—b^5F_5	33695.429	.110	.109	−.024	+.042
60 V	7531.171	6	*B*	13274.498	$a_3G_4^4$—c^3F_3	35257.351		.545	−.027	+.047
30 V	7568.925	6	*C*	13208.285	$b^5F_2^2$—b^5F_2	34547.243		.328	−.025	+.043
50 IV	7583.796	6	*B*	13182.385	b^5G_3—$b^5F_3^3$	24338.805		.396	−.006	+.011
150 V	7586.044	8	*A*	13178.479	$a^5G_5^6$—c^3F_4	34782.454		.519	−.023	+.040
25 V	7620.538	4 h	*B*	13118.827	$b^5D_2^2$—a^3D_3	38175.391		.871	−.026	+.044
30 V	7661.223	4	*A*	13049.160	$b^5F_2^2$—b^5F_4	34328.787		.204	−.026	+.044
80 IV	7664.302	8	*B*	13043.918	b^3G_4—$b^3F_3^3$	24118.854		.933	−.009	+.015
25 V	7710.390	4	*A*	12965.949	$b^5F_4^4$—b^5F_5	34039.548		.990	−.024	+.041
125 IV	7748.281	8	*A*	12902.543	b^3G_5—$b^3F_4^4$	23783.654		.563	−.012	+.020
300 V	7780.586	8 h	*B*	12848.972	$a^3G_3^4$—c^3F_2	36079.411	9.013	9.012	−.024	+.040
400 V	7832.224	6	*B*	12764.259	$a^3G_4^4$—c^3F_3	35767.603	.296	.293	−.021	+.034
6 IIA	7912.866	3	*A*	12634.176	a^5F_5—$a^7D_4^4$	6928.272		.185	−.006	+.009
700 V	7937.166	6	*A*	12595.495	$a^5G_5^5$—$b^5F_4^4$	34782.454		.537	−.026	+.042
600 V	7945.878	6	*B*	12581.685	$a^3G_4^4$—c^3F_4	35379.246		.727	−.026	+.042
20 IV	7994.473	4	*A*	12505.207						
700 V	7998.972	6	*C*	12498.174	$a^5G_4^4$—b^5F_3	35257.351	.216	.220	−.030	+.046
50 V	8028.341	6 h	*B*	12452.454	$a^3G_3^4$—c^3F_3	36079.411		.485	−.020	+.031
600 V	8046.073	6	*B*	12425.011	$a^5G_3^4$—b^5F_2	35611.656	.045	.046	−.023	+.035
10n V	8080.668	3	*A*	12371.817						
500 V	8085.200	6	*A*	12364.882	$a^5G_2^4$—b^5F_1	35856.431		.921	−.026	+.039

[a] A. S. King, Astrophys. J. **80**, 124 (1934).
[b] K. Burns and F. M. Walters, Jr., Pub. Allegheny Obs. **6**, 159 (1929).

[19] Pub. Allegheny Obs. **6**, 159 (1929).

TABLE 1.—*Interference measurements in the infrared arc spectrum of iron*—Continued

Intensity and temperature class [a]	λ Integrated light of arc in air	Number of observations	Character of line and probable error	Wave-number in vacuum	Term combination [b]	Value of lower term [b]	Wave-number arc in vacuum		Difference vacuum arc—air arc	
							Observed	Computed	λA	νcm^{-1}
10 IV	8096.874	3	*A*	12347.055						
80 V	8198.951	7	h *A*	12193.335	$a^3G_4^+$—c^3F_4	35767.603		.370	−.024	+.035
40 V	8207.767	6	h *A*	12180.238	$a^3G_3^+$—b^3F_3	35856.431		.271	−.022	+.033
1500 V	8220.406	6	*B*	12161.510	$a^3G_5^+$—b^3F_5	34843.984	.549	.554	−.030	+.044
50 V	8232.347	6	h *B*	12143.870	$a^3G_3^+$—b^3F_4	35611.656		.915	−.030	+.045
8 IV	8239.130	5	*B*	12133.873	a^3P_1—$a^3D_2^+$	19552.493		.887	−.010	+.014
30 V	8248.151	6	h C	12120.602	$a^3G_4^+$—b^3F_4	35257.351		.640	−.026	+.038
20 V	8293.527	6	*B*	12054.287						
1200 II	8327.063	6	*A*	12005.741	a^5P_2—$a^5P_1^+$	17727.011	.751	.747	−.004	+.006
200 V	8331.941	6	h *B*	11998.712	$a^3G_3^+$—b^3F_4	35379.246		.745	−.023	+.033
80 V	8339.431	7	h *A*	11987.935	$a^3G_4^+$—b^3F_3	35767.603		.968	−.023	+.033
8 V	8360.822	4	h *A*	11957.265	$a^3G_3^+$—b^3F_2	36079.411		.291	−.018	+.026
25 IV	8365.642	6	*A*	11950.375						
1200 II	8387.781	10	*B*	11918.833	a^5P_3—$a^5P_2^+$	17550.207	.840	.837	−.003	+.004
20 V	8439.603	4	h *B*	11845.648	$b^5F_4^+$—c^5F_3	36686.217		.679	−.022	+.031
300 II	8468.413	13	*A*	11805.348	a^5P_1—$a^5P_1^+$	17927.408		.350	−.001	+.002
150 II	8514.075	13	*B*	11742.035	a^5P_2—$a^5P_2^+$	17727.011		.033	+.001	−.002
8 V8	8526.685	3	h *C*	11724.670	$c^5D_4^+$—c^5D_4	39625.847		.692	−.016	+.022
15 IV	8582.267	7	*A*	11648.737	b^3G_4—$a^3G_4^+$	24118.854		.749	−.009	+.012
40 III	8611.807	12	*A*	11608.780	b^3P_1—$a^3P_0^+$	22946.860		.761	+.014	−.019
10 IV	8621.612	5	*B*	11595.578	b^3G_5—$a^3G_5^+$	23783.654		.592	−.010	+.014
600 II	8661.908	12	*A*	11541.634	a^5P_1—$a^5P_2^+$	17927.408	.638	.636	−.002	+.002
60 III	8674.751	13	*A*	11524.547	b^3P_2—$a^3P_1^+$	22838.360		.541	+.005	−.006
1500 II	8688.633	12	*A*	11506.134	a^5P_2—$a^5P_1^+$	17550.207	.144	.145	−.008	+.011
25 IV	8757.192	12	*A*	11416.054	b^3P_1—$a^3P_1^+$	22946.860		.041	+.010	−.013
20n V	8764.000	10	h *B*	11407.186	$b^3F_3^+$—c^3F_3	37521.201		.219	−.025	+.033
25n V	8793.376	11	h *B*	11369.078	$b^3F_3^+$—c^3F_3	37162.787		.109	−.024	+.031
	8804.624	3	*A*	11354.554	a^3P_2—$a^3P_1^+$	18378.215		.543	+.009	−.011
250 II	8824.227	14	*A*	11329.330	a^5P_3—$a^5P_2^+$	17727.011	.338	.341	−.009	+.011
30 IV	8838.433	11	*A*	11311.120	$b^3P_0^+$—$a^3P_1^+$	23051.790		.111	+.007	−.009
60 V	8866.961	10	*A*	11274.729	$b^3F_4^+$—c^3F_4	36686.217		.756	−.021	+.027
10m V	8945.204	4	h *A*	11176.110	$c^5F_4^+$—c^5D_3	40594.453		.150	−.032	+.040
10 IV	8975.408	6	*B*	11138.500	b^3G_4—$a^5G_4^+$	24118.854		.497	+.002	−.003
200 III	8999.561	11	*A*	11108.607	b^3P_2—$a^3P_2^+$	22838.360		.605	+.002	−.002
10 V	9012.098	4	h *C*	11093.154	$c^3F_3^+$—c^3D_4	40257.367		.172	−.015	+.018
4 V	9079.599	3	h *C*	11010.683	$b^3F_3^+$—c^3F_3	37521.201		.695	−.010	+.012
50 IV	9088.326	8	*A*	11000.110	b^3P_1—$a^3P_1^+$	22946.860		.105	+.004	−.005
30 IV	9089.413	8	*B*	10998.795	b^3G_5—$a^5G_5^+$	23783.654		.800	−.004	+.005
25 IV	9118.888	8	*A*	10963.244	b^3P_2—$b^3D_2^+$	22838.360		.248	−.003	+.004
2n V	9147.800	3	h *B*	10928.594						
6 IV	9210.030	7	*B*	10854.752	b^3P_1—$b^3D_2^+$	22946.860		.748	+.003	−.004
10n V	9258.30	4	h *C*	10798.159	$b^3F_3^+$—c^3F_4	37162.787		.186	−.023	+.027
6 V	9350.46	4	h *C*	10691.730	$b^3F_4^+$—b^3F_4	36686.217		.774	−.039	+.044
3 IV	9359.420	3	*C*	10681.495	b^3F_4—$a^3D_3^+$	20641.144		.493	+.002	−.002
4 IV	9362.370	4	*C*	10678.129	a^3P_2—$a^5P_2^+$	18378.215		.137	−.007	+.008
6 IV	9372.900	7	*C*	10666.133	b^3F_4—$a^3F_4^+$	20641.144		.133	±.000	±.000
3 IV	9430.08	3	*C*	10601.46						
8n V	9513.24	4	h *C*	10508.78	$c^3F_4^+$—$18W_3$	40594.453		.784		
15n V	9569.960	4	h *A*	10446.502	$c^5F_5^+$—$28W_3$	40257.367		.545	−.040	+.043
12n V	9626.562	4	h *C*	10385.079	$c^3F_4^+$—$59W_3$	40594.453		.174	−.088	+.095
15 V	9653.143	7	h *C*	10356.483	$b^3D_3^+$—c^3F_3	38175.391		.505	−.021	+.022
100 V	9738.624	8	h *C*	10265.579	$c^5F_4^+$—$46W_3$	40257.367		.621	−.040	+.042
10 V	9753.129	4	h *A*	10250.311	$b^3D_2^+$—c^3F_3	38678.075		.348	−.035	+.037
10 V	9763.450	2	h *C*	10239.48	$c^5F_1^+$—$9W_3$	41130.663		.521		
12 V	9763.913	5	h *C*	10238.990	$c^5F_2^+$—$25W_3$	40594.453		9.032	−.040	+.042
8n V	9800.335	4	h *C*	10200.938	$c^3F_2^+$—$14W_3$	41018.056		1.003	−.063	+.065
12 V	9861.793	6	h *C*	10137.367	$c^5F_3^+$—$59W_3$	40842.185		.442	−.073	+.075
15 V	9889.082	6	h *C*	10109.393	$c^5F_3^+$—$28W_3$	40594.453		.459	−.065	+.066
30 V	10065.080	8	h *C*	9932.621	$b^3D_1^+$—c^3F_2	38995.771		.652	−.031	+.031
40 V	10145.601	8	h *C*	9853.790	$b^3D_2^+$—c^3F_3	38678.075		.821	−.031	+.031
50 V	10216.351	8	h *C*	9785.551	$b^3D_3^+$—c^3F_4	38175.391		.582	−.032	+.031

[a] A. S. King, Astrophys. J. **80**, 124 (1934).
[b] K. Burns and F. M. Walters, Jr., Pub. Allegheny Obs. **6**, 159 (1929).

A glance at table 1 shows that most of the infrared lines of iron require energies of 4 to 6 electron volts for their excitation. This accounts, at least qualitatively, for the low intensity of the arc flame at the center and near the anode since these radiations are strongly excited only near the cathode where the potential gradient is largest. Because these infrared lines involve high-excitation energies, they may be expected to exhibit relatively large pressure displacements, and because they are strongly excited only in the proximity of the cathode it may be assumed that they will show the so-called pole effect, which is undoubtedly to be interpreted as a true Stark effect arising from high electric fields near this electrode.

Precise measurements of the effect of pressure on the spectrum of the iron arc were made by Babcock [20] who compared the wave lengths of 130 iron lines (3896 to 6678 A) from the international arc with those from a vacuum arc. He found that increase of pressure displaces all classes of iron lines toward longer waves, the shift is the same for all lines of the same multiplet, and the amount of the displacement is a function of the spectral term magnitudes, being determined primarily by the upper term. These pressure effects are most conveniently expressed in wave numbers in which case they are correlated directly with the depression of spectral terms. The observed depressions due to a change of pressure from 0 to 1 atmosphere were published by Babcock for 34 iron terms, assuming that the depression for the ground term is zero, and general formulas were given for computing the depressions of any other iron terms.

Data in the last column of table 1 may be compared with Babcock's term depression data, but it must be remembered that my measurements relate to integrated arc light while his refer to a narrow central zone of a long arc which is free from pole-effect. Such a comparison is shown in table 2 for some of the prominent infrared multiplets of iron.

TABLE 2.—*Comparison of multiplet displacements in the iron arc*

Multiplet	Vacuum arc [a] minus integrated arc in air cm^{-1} (A)	Term depressions [b] cm^{-1}			Difference cm^{-1} (B)−(A)
		Lower	Higher	Difference higher-lower (B)	
$b^5D°—b^5F$	+0.040	+0.015	+0.033	+0.018	−0.022
$b^5F°—b^5F$	+.040	+.013	+.033	+.020	−.020
$a^5G°—c^5F$	+.037	+.014	+.029	+.015	−.022
$a^5G°—b^5F$	+.039	+.011	+.033	+.022	−.017
$a^5P—a^5P°$	+.006	+.003	+.012	+.009	−.003
$b^3P—a^3P°$	−.009	+.004	+.013	+.009	+.018
$b^3F°—c^3F$	+.032	+.015	+.029	+.014	−.018
$b^3D°—c^3F$	+.031	+.015	+.039	+.014	−.017

[a] K. Burns and F. M. Walters, Pub. Allegheny Obs. **6**, 159 (1929).
[b] H. D. Babcock, Astrophys. J. **67**, 167 (1928).

The displacements in the second column are seen to be in qualitative agreement with differences of term depressions. This agreement can be regarded as exact if the differences in the last column are interpreted as evidence for pole effect (Stark effect) in the integrated light from the arc. This interpretation is justified by the fact

[20] Astrophys. J. **67**, 167 (1928).

that Stark effect may be expected in these high-excitation lines, and that, in general, the differences here shown are of the same sign and the same order of magnitude as the so-called pole effect for other groups of iron lines. These pole effects have been identified especially with 2 groups of lines, the *d* group exhibiting a greater wave length near the pole than at the center of the arc, and the *e* group a smaller wave length at the pole. Accordingly, we may say that multiplet $a^5P - a^5P^\circ$ listed in table 2 shows little or no pole effect, while the remaining multiplets belong to group *d*, except $b^3P - a^3P^\circ$ which behaves like group *e*. In other words, most of the infrared iron lines are displaced to longer waves in high electric fields, but one multiplet is outstanding in that its lines are shifted to shorter waves.

The hazy character of so many infrared iron lines, as noted in table 1, appears to be a function primarily of the excitation energy or corresponding pressure shift and broadening, since almost without exception only lines whose lower terms exceed about 36000 give interferences which are hazy or less sharp than the others. The limiting order of interference for these lines is relatively low, many of them being difficult to measure when the order exceeds 30000 waves. However, in spite of the fact that integrated arc light contains line displacements due to pressure and to Stark effects, my experience indicates that the degree of reproducibility in measuring wave lengths in this source is of the same order as that obtainable either with the international arc or with the vacuum arc. The latest modification of the international arc was designed to eliminate pole effects from the measurements but it is still afflicted with pressure effects and is entirely useless in the infrared on account of the low intensity. The vacuum arc is free from both pressure and Stark effects, and is undoubtedly the correct source to use for producing truly "fundamental" wave lengths. From the standpoint of stability, reproducibility, and intensity, the integrated light from an iron arc at atmospheric pressure is not inferior to the other types of iron sources, and it certainly deserves consideration as a modification of the present international iron arc as a source of infrared standards conveniently obtainable with the identical equipment which now yields secondary standards of wave length in the interval 3370 to 6750 A.

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A MAXWELL TRIANGLE YIELDING UNIFORM CHROMATICITY SCALES

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ABSTRACT

A colorimetric coordinate system has been found by trial and error whose Maxwell triangle has the useful property that the length of any line on it is a close measure of the chromaticity difference between the stimuli represented at the extremes of the line. Such accurate chromaticity scales may be derived from this triangle merely by stepping off equal intervals on it that it has been called the "uniform-scale triangle." The definition of the system is given, and also a comparison of experimental sensibility data with corresponding data derived from the triangle. An important application of this coordinate system is its use in finding from any series of colors the one most resembling a neighboring color of the same brilliance, for example, the finding of the nearest color temperature for a neighboring non-Planckian stimulus. The method is to draw the shortest line from the point representing the non-Planckian stimulus to the Planckian locus.

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I. INTRODUCTION

In a previous paper [1] experimental data on chromaticity sensibility were related to the (r, g)–plot of the OSA tristimulus coordinate system. The method of relation was called the "square construction" because by that method the locus of points representing chromatic colors equally distinguishable from any one given color of the same brilliance is a square centered on the point representing the given color.

The present method of relating chromaticity sensibility to the Maxwell triangle is the graphically more convenient "circle construction." When applied to the OSA colorimetric coordinate system, the circle construction resulted in poorer agreement with sensibility data than the analytically simple square construction. A new coordinate system has been derived, however, for the sole purpose of making use of the circle construction to the best advantage on the equilateral Maxwell triangle. This paper gives the definition of the new tristimulus coordinate system, shows the degree of agreement obtained with both the data previously assembled and those which have become available since, and points out the uses to which the Maxwell triangle of this coordinate system may be put.

II. MATHEMATICAL ANALYSIS

If any two color stimuli specified by points (r_1, g_1, b_1) and (r_2, g_2, b_2) on the equilateral tringle are compared, with brightnesses equalized, the circle construction states that the chromaticity difference, ΔE, between them is proportional to the distance, D, between the points representing them, or:

$$K\Delta E=D \tag{1}$$

where K is a constant of proportionality dependent on the unit (least perceptible difference, probable error and so on) in which ΔE is expressed and on the experimental conditions such as field size and field brightness.[2]

From the geometry of the equilateral triangle the distance, D, may be expressed in terms of the differences between the trilinear coordinates, writing Δr, Δg, Δb as abbreviations for r_1-r_2, g_1-g_2, b_1-b_2, respectively, thus:

$$D=\sqrt{2[(\Delta r)^2+(\Delta g)^2+(\Delta b)^2]/3} \tag{2}$$

where unit D is the altitude of the triangle. This relation may also be written in a form particularly convenient for dealing with a number of distances in the same direction. Let Δv be any one of Δr, Δg, Δb, and Δq be either of the remaining two, then:

$$D=\frac{2\Delta v}{\sqrt{3}}\sqrt{(\Delta q/\Delta v)^2+(\Delta q/\Delta v)+1} \tag{2a}$$

$(\Delta q/\Delta v)$ constant being the condition for distances in the same direction on the triangle.

[1] D. B. Judd, *Chromaticity sensibility to stimulus differences*, J. Opt. Soc. Am. **22**, 72 (1932).
[2] J. Opt. Soc. Am. **22**, 87 (1932).

In a few cases where the circle construction is analytically inconvenient, the nearly equivalent hexagon construction has been substituted. According to this construction:

$$\left.\begin{aligned} K\Delta E &= \Delta c \\ &= |\Delta r|, |\Delta g|, \text{ or } |\Delta b|, \text{ whichever is the largest;} \\ &= (|\Delta r| + |\Delta g| + |\Delta b|)/2 \end{aligned}\right\} \quad (1a)$$

where the absolute value signs ($|\ |$) indicate that the differences are to be taken all greater than zero. The hexagon construction differs from the circle construction by a factor varying from $2/\sqrt{3}$ to 1, or by a maximum of about 15 percent. It may be substituted for the circle construction if differences of this size are not significant.

III. MIXTURE DIAGRAM

The coordinate system found by trial and error to yield the best agreement with chromaticity sensibility may conveniently be defined as a projective transformation of the 1931 ICI standard coordinate system for colorimetry.[3] If $\bar{x}$, $\bar{y}$, $\bar{z}$ be the tristimulus specifications of a given color stimulus on the ICI system, then $\bar{r}$, $\bar{g}$, $\bar{b}$, the tristimulus specifications on the uniform-scale system, may be found as:

$$\left.\begin{aligned} \bar{r} &= 3.1956\,\bar{x} + 2.4478\,\bar{y} - 0.1434\,\bar{z} \\ \bar{g} &= -2.5455\,\bar{x} + 7.0492\,\bar{y} + 0.9963\,\bar{z} \\ \bar{b} &= 0.0000\,\bar{x} + 0.0000\,\bar{y} + 1.0000\,\bar{z} \end{aligned}\right\} \quad (3)$$

The reverse transformation is given by:

$$\left.\begin{aligned} \bar{x} &= 0.24513\,\bar{r} - 0.08512\,\bar{g} + 0.11996\,\bar{b} \\ \bar{y} &= 0.08852\,\bar{r} + 0.11112\,\bar{g} - 0.09802\,\bar{b} \\ \bar{z} &= 0.00000\,\bar{r} + 0.00000\,g + 1.00000\,\bar{b} \end{aligned}\right\}$$

For convenience in checking arithmetical results the coefficients of these transformation equations are given to at least three more decimal places than would be significant from the trial-and-error adjustment to experimentally known chromaticity sensibility.

It may be noted that the only way in which better agreement with sensibility data may be effected is by a transformation which alters the shape of the spectrum locus. Transformations which merely displace the locus with respect to the triangle, or reorient it, or expand or contract it uniformly do not at all change the agreement. The system defined by eq 3 is one of many possible systems giving this particular shape to the spectrum locus. The luminosity coefficients are $L_r = 0.08852$, $L_g = 0.11112$, $L_b = -0.09802$.

The uniform-scale system is more closely allied to the OSA coordinate system[4] by derivation than to the ICI system. The coefficients of transformation between the uniform-scale system and the OSA system are:

$$\left.\begin{aligned} &\text{OSA to uniform-scale} \\ &\quad 1,\ 0,\ 0.1 \\ &\quad 0,\ 1,\ 0.1 \\ &\quad 0,\ 0,\ 0.2 \\ &\text{Uniform-scale to OSA} \\ &\quad 1,\ 0,\ -0.5 \\ &\quad 0,\ 1,\ -0.5 \\ &\quad 0,\ 0,\ 5.0 \end{aligned}\right\} \quad (3a)$$

[3] Proc. 8th session, International Commission on Illumination, Cambridge, pages 19 to 29 (September 1931). D. B. Judd, *The 1931 ICI standard observer and coordinate system for colorimetry*, J. Opt. Soc. Am. **23**, 359 (1933). T. Smith and J. Guild, *The CIE colorimetric standards and their use*, Trans. Opt. Soc. **33**, 73 (1931-32).

[4] J. Opt. Soc. Am. **22**, 102 (1932).

These coefficients have been used in transforming data on the OSA basis referring to Lovibond glasses, but in the other comparisons presented, the 1931 ICI standard observer and eq 3 have been used.

Figure 1 shows the spectrum locus and the Planckian locus on the equilateral Maxwell triangle of the new uniform-scale system. A given color stimulus ($\bar{r},\bar{g},\bar{b}$) is represented on this triangle according to its trilinear coordinates (r,g,b) which are fractional parts of the total, $\bar{r}+\bar{g}+\bar{b}$, and refer to distances perpendicular to a side of the triangle. Table 1 gives the trilinear coordinates from which the spectrum locus and the Planckian locus on figure 1 have been plotted; it also gives the trilinear coordinates of the recombined equal-energy spectrum which is the basic stimulus of the ICI system, Abbot-Priest sunlight,[5] mean noon sunlight from Abbot's data as averaged by Davis and Gibson,[6] and sunlight outside the atmosphere from Abbot's data.[7]

TABLE 1.—*Trilinear coordinates on the uniform-chromaticity-scale triangle*

Observer: 1931 ICI standard

PART 1, FOR THE SPECTRUM

Wave length	r	g	b	Wave length	r	g	b
mμ				mμ			
380	.2681	0.2437	0.4881	550	0.3918	0.6072	0.0009
				560	.4404	.5592	.0004
410	.2648	.2461	.4891	570	.4995	.5003	.0002
				580	.5708	.4291	.0002
430	.2575	.2584	.4841	590	.6532	.3467	.0001
440	.2495	.2761	.4744				
				600	.7388	.2611	.0001
450	.2363	.3049	.4588	610	.8169	.1830	.0001
460	.2173	.3493	.4334	620	.8776	.1224	.0001
470	.1961	.4226	.3813	630	.9206	.0793	.0000
480	.1833	.5353	.2814	640	.9521	.0478	.0000
490	.1906	.6467	.1627				
				650	.9728	.0272	.0000
500	.2147	.7092	.0761				
510	.2440	.7249	.0312	700	1.0000	.0000	.0000
520	.2784	.7103	.0113				
530	.3145	.6805	.0050				
540	.3511	.6467	.0022				

PART 2, FOR THE PLANCKIAN RADIATOR

Color temperature	r	g	b	Color temperature	r	g	b
°K				°K			
100	1.0000	0.0000	0.0000	2,848	0.5434	0.4239	0.0327
300	.9981	.0019	.0000	3,500	.5103	.4427	.0470
600	.9237	.0763	.0000	4,800	.4696	.4598	.0706
1,000	.7906	.2086	.0008	6,500	.4409	.4672	.0920
1,500	.6809	.3140	.0051	10,000	.4142	.4699	.1159
1,900	.6242	.3640	.0118	24,000	.3898	.4685	.1417
2,360	.5783	.4001	.0216	∞	.3769	.4663	.1568

PART 3, FOR SOME MISCELLANEOUS STIMULI

	r	g	b
Abbot-Priest sunlight	0.4607	0.4665	0.0728
Abbot-Davis-Gibson mean noon sunlight	.4572	.4688	.0740
Sunlight outside atmosphere (Abbot)	.4402	.4713	.0885
Equal energy spectrum recombined	.4583	.4583	.0833

[5] I. G. Priest, *A precision method for producing artificial daylight.* Phys. Rev. [2], **11**, 502 (1918); J. Opt. Soc. Am. and Rev. Sci. Inst., **12**, 479 (1926). D. B. Judd, *Reduction of data on mixture of color stimuli.* BS J. Research, **4**, 525 (1930) RP163.

[6] R. Davis and K. S. Gibson, *Filters for the reproduction of sunlight and daylight and the determination of color temperature.* Misc. Pub. BS 114, 16 (1931).

[7] See table 1 in article cited in footnote 6.

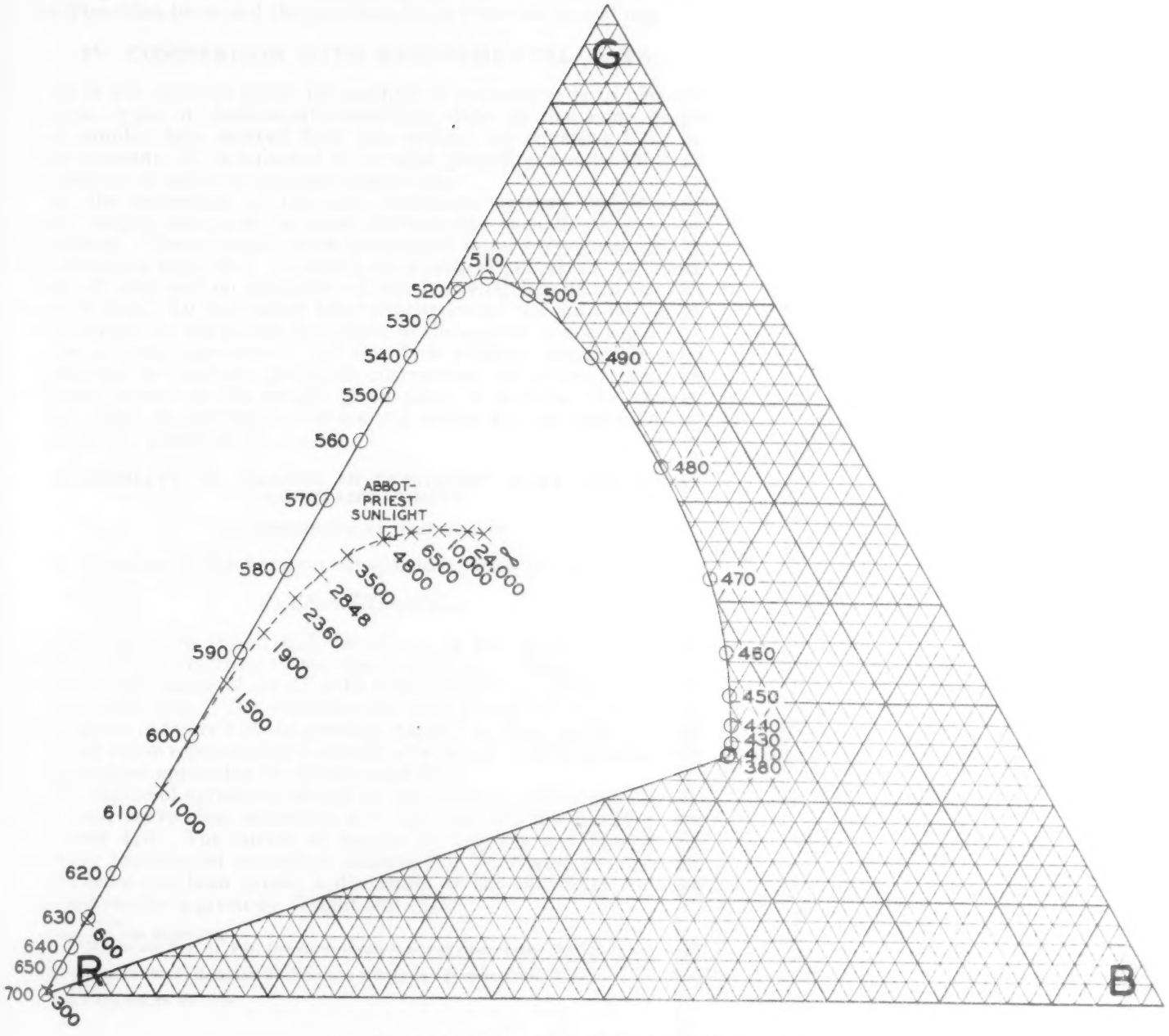

FIGURE 1.—*The uniform-chromaticity-scale triangle.*

Wave length along the spectrum locus is indicated in millimicrons; color temperature along the Planckian locus is given in degrees Kelvin.

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On this triangle equal chromaticity intervals are represented by lines of nearly equal length. An outstanding difference between this and the usual Maxwell triangle is the smaller distance between the Planckian locus and the spectrum locus from 550 to 600 mμ.

IV. COMPARISON WITH EXPERIMENTAL DATA

As in the previous paper the method of comparison is to plot the various types of chromaticity-sensibility data on the same graph with similar data derived from the triangle by equation 1 or 1a. The constant, K, is adjusted to a value providing nearly the best agreement in order to facilitate comparison.

In the derivation of the new coordinate system, considerably more weight was given to some chromaticity-sensibility data than to others. These weights were determined in no very systematic or quantitative way; they depended on a critical survey of the whole body of data and on estimates of relative reliability of the various sets of data. Of the rather large proportion of the data not taken into account in the actual derivation of the system, much was found to be in good agreement. All the data yielding sufficiently good agreement to warrant graphical comparison are shown, however, without regard to the weight given them in deriving the system. Data which do not agree well are not shown but are mentioned at appropriate places in the text.

1. SENSIBILITY TO CHANGE IN DOMINANT WAVE LENGTH AT CONSTANT PURITY

(a) SENSIBILITY AT UNIT PURITY

By equation 1a the hexagon construction yields for this case:

$$d\lambda/dE = K/(dc_h/d\lambda)_{p=1} \tag{4}$$

where λ is wave length and $(dc_h/d\lambda)_{p=1}$ is the largest of $|dr/d\lambda|$, $|dg/d\lambda|$, $|db/d\lambda|$ referring to the spectrum locus. Figure 2 compares experimental values of $d\lambda/dE$ with $0.007/(dc_h/d\lambda)_{p=1}$ which is shown by the solid line. The experimental data indicated by points are those given in figure 3 of the previous paper;[8] to these has been added a dotted curve representing the result of a recent careful investigation with modern apparatus by Wright and Pitt.[9]

The degree of agreement shown by figure 2 is good but not perfect. The solid curve rises somewhat too high near 510 mμ and stays too low near 470. The curves of results by Laurens and Hamilton[10] showing pronounced secondary minima not duplicated in the solid curve have not been given; a discussion of the reliability of these omitted results is given by Wright and Pitt.[11]

[8] J. Opt. Soc. Am. **22**, 89 (1932).
[9] W. D. Wright and F. H. G. Pitt, *Hue-discrimination in normal colour-vision*. Proc. Phys. Soc. **46**, 459 (1934).
[10] H. Laurens and W. F. Hamilton, *The sensibility of the eye to differences in wave length*. Am. J. Physiol. **65**, 547 (1923).
[11] Proc. Phys. Soc. **46**, 466 (1934).

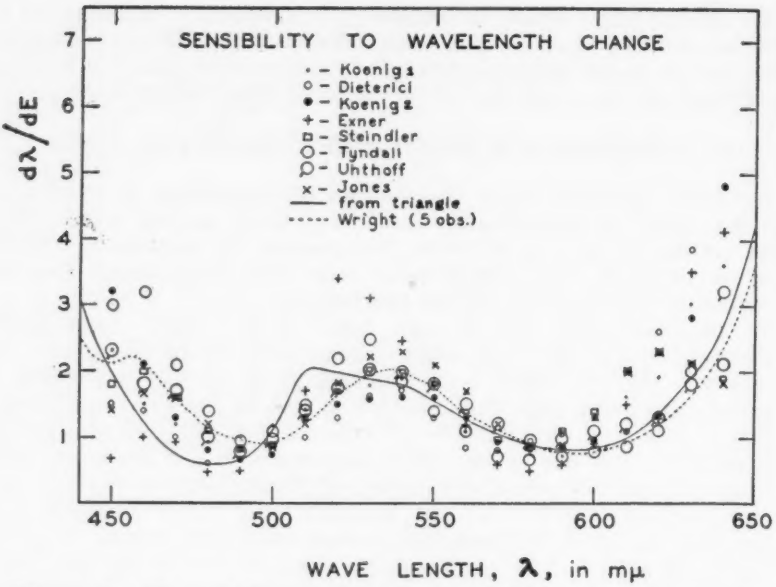

FIGURE 2.—*Chromaticity sensibility to wave-length change in the spectrum.*

(b) RATIO OF SENSIBILITY AT PURITY, p, TO THAT AT UNIT PURITY

Analogous to equation 9a of the previous paper extended to the general choice of heterogeneous stimulus [12] the hexagon construction yields:

$$\frac{(d\Lambda/dE)_p}{(d\lambda/dE)_{p=1}} = \frac{[s_h(1-p)+s_w p]^2(dc_h/d\lambda)}{s_w p\,\{[s_h(1-p)+s_w p](dc_h/d\lambda)+(1-p)(c_w-c_h)(ds_h/d\lambda)\}} \quad (5)$$

where Λ is dominant wave length, s_h is an abbreviation for $rL_r+gL_g+bL_b$ for the spectrum at wave length, Λ, s_w is an abbreviation for the similar sum referring to the heterogeneous stimulus ("white light"), and c as in equation 1a is either r, g, or b. As discussed in the previous paper, care must be taken in applying this formula because of the multiple definition of c_h. In the numerator, c_h is taken as r, g, or b according as $dr/d\lambda$, $dg/d\lambda$, or $db/d\lambda$ has the greatest absolute value for the spectrum ($p = 1$). In the denominator, c_h is chosen as r, g, or b according to which choice makes the absolute value of the denominator the greatest. For most values of wave length, c_h is the same in the numerator and denominator, but not at all wave lengths.

In figure 3 are shown the experimental values of this ratio obtained by Tyndall [13] (circles) and those obtained by Watson [14] (crosses). The data by Watson shown on plots marked 530, 585, and 630 refer to wave lengths 527, 589, and 632mμ, respectively. The curves shown were obtained from equation 5 with Abbot-Priest sunlight as the heterogeneous stimulus, that is, for $r_w=0.461$, $g_w=0.466$, $b_w=0.073$.

[12] D. B. Judd, *A general formula for the computation of colorimetric purity.* BS J. Research **7**, 827 (1931) RP377; see equation 14.

[13] E. P. T. Tyndall, *Chromaticity sensibility to wave-length difference as a function of purity.* J. Opt. Soc. Am. **23**, 15 (1933).

[14] W. Watson, *Note on the sensibility of the eye to variations of wave length.* Proc. Roy. Soc. B. **84**, 118 (1911).

This choice was made because the heterogeneous stimulus used by Tyndall was a color match for Abbot-Priest sunlight; that used by Watson was similar but not definitely known.

It will be noted from figure 3 that the agreement at three dominant wave lengths (455, 490, and 630 mμ) is nearly perfect. In the other three cases the experimentally found relation is similar to that yielded by the triangle but not identical.

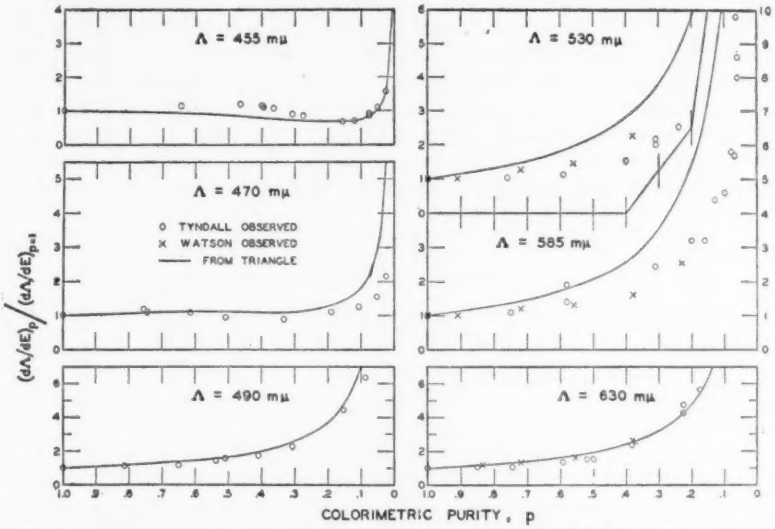

FIGURE 3.—*Chromaticity sensibility to dominant-wave-length change as a function of purity.*

2. SENSIBILITY TO CHANGE IN PURITY, DOMINANT WAVE-LENGTH CONSTANT

(a) SENSIBILITY AS A FUNCTION OF PURITY

Analogous to equation 10a of the previous paper extended as was equation 5 to the general choice of heterogeneous stimulus it is seen from equations 1 and 2a that the circle construction yields:

$$\left(\frac{dp}{dE}\right)_{\Lambda\,\text{constant}} = \frac{K}{2}\sqrt{\frac{3}{(\Delta q/\Delta v)^2+(\Delta q/\Delta v)+1}}\,\frac{[s_h(1-p)+s_w p]^2}{s_h s_w (v_h - v_w)} \qquad (6)$$

where, as in equation 2a, v is any one of r, g, b, and q is either of the remaining two; Δv may be evaluated conveniently here as $v_h - v_w$, v_h referring to the spectrum at wave length, Λ, and v_w to the heterogeneous stimulus; Δq similarly may be found as $q_h - q_w$.

In figure 4 are shown a number of experimental determinations of this quantity by Donath [15] (circles) and a determination by Judd [16] (crosses). In figure 5 are shown all of the published experimental data on this case in the recent paper by Martin, Warburton, and Morgan.[17] The curves in figures 4 and 5 refer to wave lengths

[15] F. Donath, *Die funktionale Abhängigkeit zwischen Reiz und Empfindung bei der Farbensättigung.* Neue Psych. Stud. **2**, 143 (1926).
[16] J. Opt. Soc. Am. **22**, 94 (1932).
[17] L. C. Martin, F. L. Warburton, and W. J. Morgan, Determination of the Sensitiveness of the Eye to Differences in the Saturation of Colours, Medical Research Council, Reports of the Committee upon the Physiology of Vision, XIII, Special Report Series, no. 188, London (1933).

approximately but not identically those of the experimental results and were obtained from equation 6, those in figure 4 with K adjusted in each case, those in figure 5 with K adjusted to 0.015 throughout. Values of K referring to Donath's work which was done with an improved technic involving rotating disks viewed by both eyes vary from 0.0014 to 0.0023; the value of K for Judd's result referring to a 2° field viewed with one eye is 0.011. The marked dependence of K on observing conditions was discussed in the previous paper.

From figure 4 it may be seen that with one exception (550 mμ) the experimental determination of the function agrees with that yielded by the triangle. The data shown in figure 5, being results of single settings rather than averages of from 4 to 10 settings, yield points that are more scattered than those of the previous figures. In general there is fair agreement between the observed function and that obtained from the triangle. Most of the points for 650 and 680 mμ

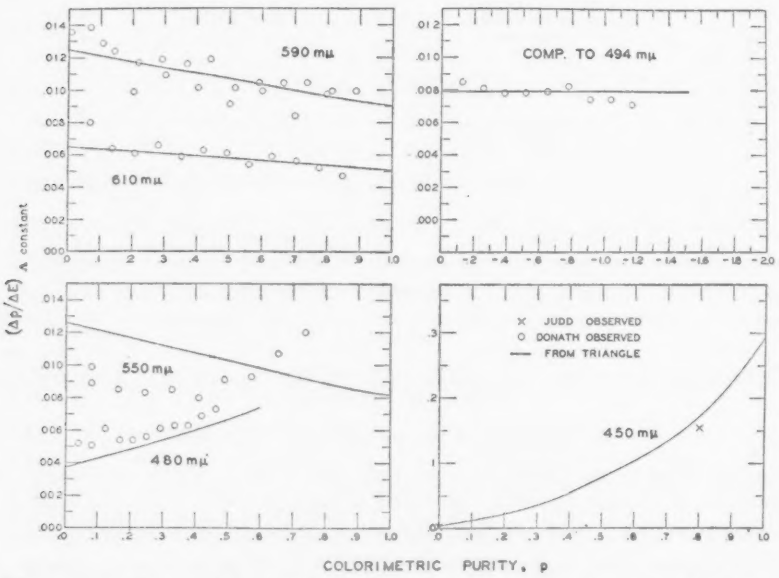

FIGURE 4.—*Chromaticity sensibility to purity change as a function of purity.*

are higher than the curve; perhaps some of the discrepancy at these wave lengths is ascribable to a low field brightness for this extreme spectral region. There is a general tendency throughout for the experimental data to indicate a rise in dp/dE with purity for low purities. Some of this rise has been ascribed by the authors to a fatigue effect combined with the fact that the majority of the step-by-step settings progressed upward from zero purity; the settings in which the progression was in the opposite direction substantiate this view. It is probably significant that of all wave lengths investigated, that (460 mμ) yielding the most consistent rise for low purities is the only one for which the triangle also indicates a rise. Note also that the observed function for 546 mμ in figure 5 is convex upward while that in figure 4 for 550 mμ is convex downward, the average being in fair agreement with the function computed from the triangle.

Data by Nutting and Jones,[18] and Jones and Lowry[19] deviate considerably from each other and from the functions yielded by the triangle; they are not shown graphically. Possible sources of error in these sets of data have already been discussed.[20]

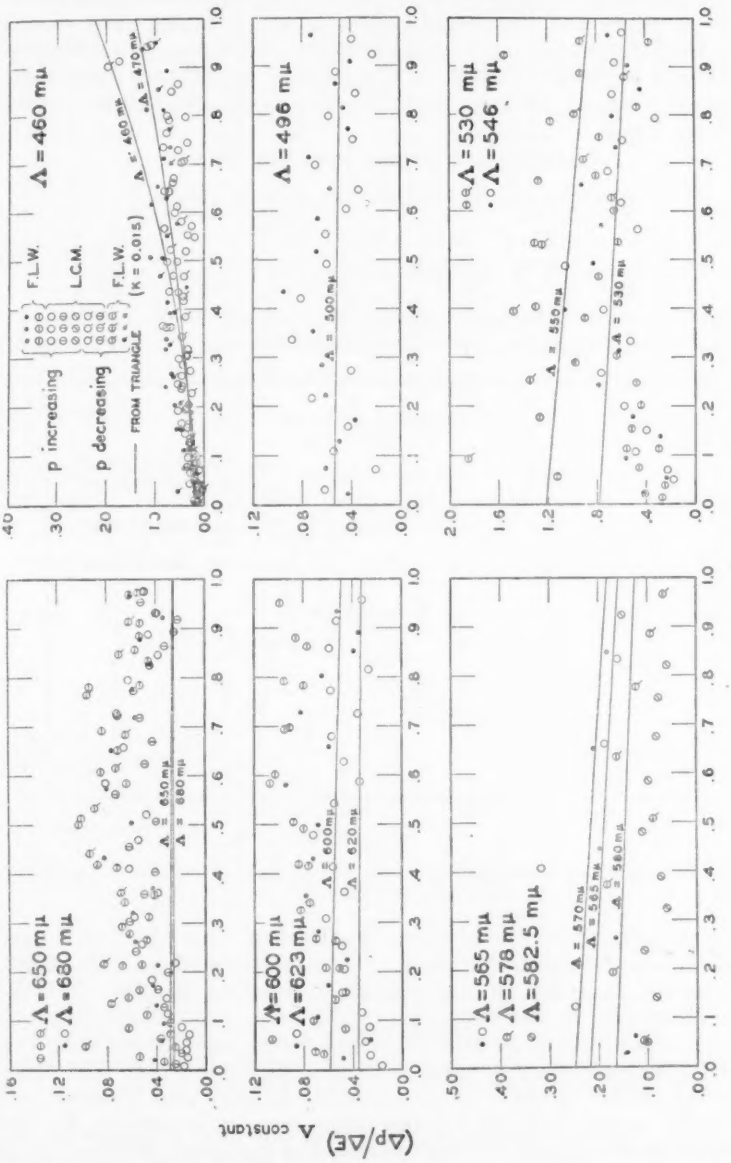

FIGURE 5.—*Chromaticity sensibility to purity change as a function of purity.*

Data by Judd[21] obtained through a different means (Lovibond yellow glasses) than other sets cited here deviate from the function

[18] P. G. Nutting, *The retinal sensibilities related to illuminating engineering.* Trans. Illum. Eng. Soc. **11**, 16 (1916).
[19] L. A. Jones, and E. M. Lowry, *Retinal sensibility to saturation differences.* J. Opt. Soc. Am. and Rev. Sci. Inst., **13**, 25 (1926).
[20] J. Opt. Soc. Am. **22**, 95 (1932); see also footnote 17, p. 47.
[21] D. B. Judd, *Saturation scale for yellow colors* J. Opt. Soc. Am. **23**, 35 (1933).

indicated by the triangle by a factor of about 2.5. Reexamination of these data has shown that an appreciable part of the deviation can be ascribed to the two-millimicron dominant-wave-length variation from one end of the Lovibond-yellow locus to the other which was previously considered negligible. These data, therefore, give a saturation scale along the Lovibond-yellow locus, but not very exactly the scale for dominant wave length constant at 575 mμ; hence they are not compared with the triangle in the form of dp/dE as a function of p, but as dN''/dE as a function of N'', the Lovibond-yellow number (see later section).

(b) SENSIBILITY NEAR ZERO PURITY

From eq 6 it is seen that the circle construction yields:

$$\left(\frac{dp}{dE}\right)_{p\to 0}=\frac{K}{2}\sqrt{\frac{3}{(\Delta q/\Delta v)^2+(\Delta q/\Delta v)+1}}\left[\frac{s_h}{s_w(v_h-v_w)}\right] \qquad (6a)$$

In figure 6 are shown experimental determinations of this quantity for a number of dominant wave lengths by Priest and Brickwedde [22]

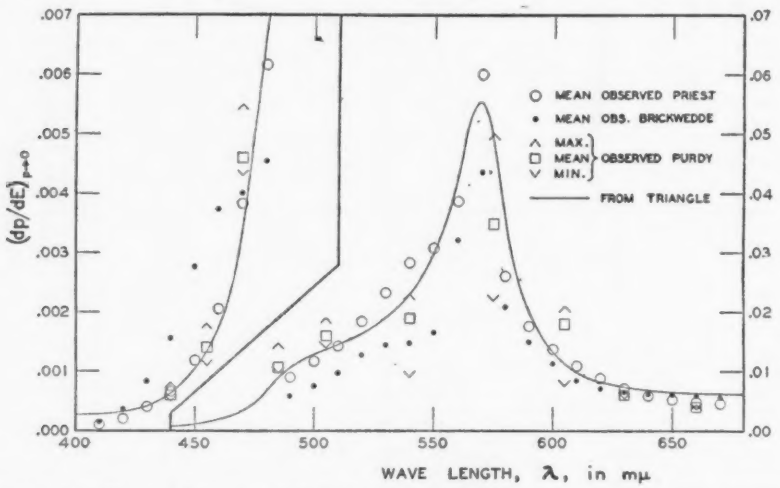

FIGURE 6.—*Chromaticity sensibility to purity change near zero purity as a function of dominant wave length.*

and by Purdy;[23] results by Martin, Warburton, and Morgan [24] agree well with these and are not shown. These experimental values have been corrected to refer to the visibility function of the 1931 ICI standard observer on the assumption that the true visibility of the three observers is the experimental mean found by Gibson and Tyndall.[25] This assumption is known to be closely correct for Priest, who was one of the 52 observers studied by Gibson and Tyndall; and it is probably nearly correct for the other two (Brickwedde, Purdy). The correction was made by multiplying the reported purities by the ratio of standard ICI visibility to experimental visibility (V_{ICI}/V_{exp}).

[22] I. G. Priest and F. G. Brickwedde, *The minimum perceptible colorimetric purity as a function of dominant wave length with sunlight as neutral standard.* J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 306 (1926); see also footnote 1, p. 42.

[23] D. McL. Purdy, *On the saturations and chromatic thresholds of the spectral colours.* Brit. J. Psych. (Gen. Sec.) **21**, pt. 3, 283 (1931).

[24] See footnote 17, p. 47.

[25] K. S. Gibson and E. P. T. Tyndall, *Visibility of radiant energy.* BS Sci. Pap. **19**, 131 (1923) S475. See first column of their table 3, p. 174.

This gives the least perceptible colorimetric purity of the field set by the observer as if analyzed photometrically by the standard observer.

In addition to this correction Purdy's values were multiplied by 0.20 to facilitate comparison with the Priest-Brickwedde values. The larger values found by Purdy are attributable to the fact that the size of field used by him (1.5° circular) was less than that used by Priest and Brickwedde (4° square).

The solid curve represents the right-hand member of eq 6a with Abbot-Priest sunlight taken as the heterogeneous stimulus, that is, for $r_w=0.461$, $g_w=0.466$, $b_w=0.073$. This choice was made because Priest and Brickwedde used this heterogeneous stimulus, and because Purdy used one nearly like this. It will be noted that the agreement shown between the corrected experimental results and those from the triangle is good. The uncorrected purities are higher than the plotted values between 400 and 440 mμ by a factor varying from 3 to 10. The good agreement obtained with the purities corrected on the basis of the Gibson-Tyndall experimental visibility suggests that those values may be more representative than the standard values.

(c) NUMBER OF STEPS BETWEEN ZERO AND UNIT PURITY AS A FUNCTION OF WAVE LENGTH

According to the circle construction the number of just noticeable chromaticity steps between zero and unit purity is proportional to the distance on the triangle between the point representing the hetero-

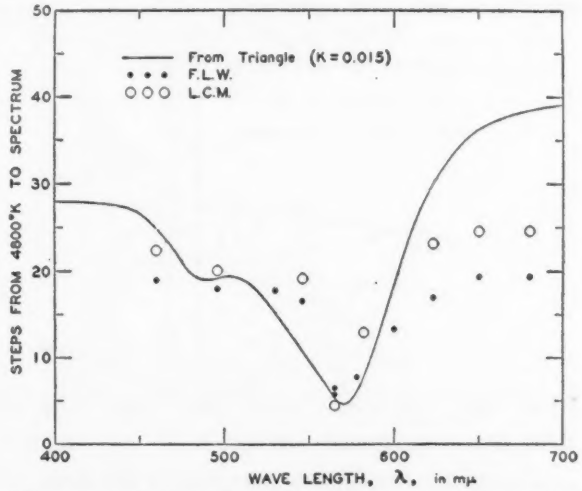

FIGURE 7.—*Number of chromaticity steps from a Planckian radiator at 4,800° K to the spectrum as a function of dominant wave length.*

geneous stimulus and the spectrum locus. From eq 1 and 2 this number may be written:

$$\Delta E=(1/K)\sqrt{2[(\Delta r)^2+(\Delta g)^2+(\Delta b)^2]/3} \qquad (7)$$

where $\Delta r=r_h-r_w$, $\Delta g=g_h-g_w$, $\Delta b=b_h-b_w$.

Figure 7 shows this number determined experimentally by Warburton and Martin [26] for a number of dominant wave lengths with the

[26] See footnote 17, p. 47.

heterogeneous stimulus a close color match for a Planckian radiator at 4,800° K.

The curve on figure 7 gives the right-hand member of eq 7 as a function of dominant wave length for the heterogeneous stimulus used by Warburton and Martin (r_w=0.470, g_w=0.460, b_w=0.070). As in figure 5, the constant, K, is taken as 0.015. The agreement is only fair, but it may be worth noting that Martin and Warburton found more steps than indicated by the curve for the brighter part of the spectrum and fewer steps for the extremes of the spectrum. Perhaps more steps would have been found at the extremes if examined at the same field brightness as the middle portion.

3. SENSIBILITY TO CHANGE IN COLOR TEMPERATURE

An empirical formula for sensibility to change in color temperature, θ, has already been found and checked [27] over a considerable range (1,800° to 11,000° K) of color temperature:

$$d(1/\theta)/dE = \text{a constant} \tag{8}$$

This relation has been partially responsible for the proposal that reciprocal temperature be used instead of temperature for color specification of illuminants.[28]

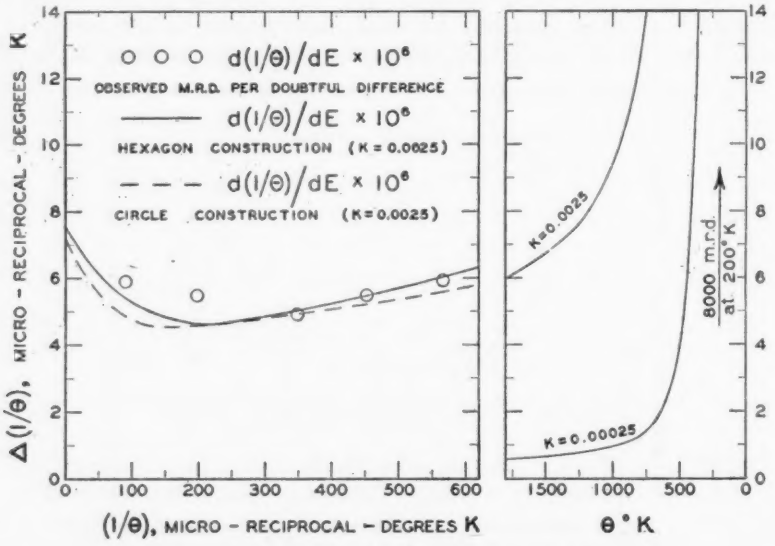

FIGURE 8.—*Sensibility to color-temperature change.*

From equation 1a it is seen that the hexagon construction yields:

$$d(1/\theta)/dE = Kd(1/\theta)/dc \tag{9}$$

Figure 8 shows (solid curve) the right-hand member of eq 9 as a function of temperature for low temperatures (0 to 1,800° K) and as a function of reciprocal temperature for high temperatures (1,600° K

[27] D. B. Judd, *Sensibility to color-temperature change as a function of temperature.* J. Opt. Soc. Am. **23,** 7 (1933).

[28] I. G. Priest, *A proposed scale for use in specifying the chromaticity of incandescent illuminants and various phases of daylight.* J. Opt. Soc. Am. **23,** 41 (1933).

up, or from zero to 625 micro-reciprocal-degrees). Although this curve is far from being horizontal over the entire range, it is nearly horizontal over the range (1,800° to 11,000° K or from about 560 to 90 micro-reciprocal-degrees) to which equation 8 applies.

Figure 8 also shows (circles) the data by means of which equation 8 was verified. It is seen that the hexagon construction is also closely verified by these data. The agreement is close enough to raise the question whether the approximate hexagon construction should not be replaced by the circle construction which, from equations 1 and 2, yields:

$$\frac{d(1/\theta)}{dE}=\frac{\sqrt{6}Kd(1/\theta)}{2\sqrt{(dr)^2+(dg)^2+(db)^2}} \tag{10}$$

where *dr*, *dg*, and *db* refer to small differences along the Planckian locus. The right-hand member of equation 10 is represented on figure 8 by the dotted curve. It is seen that about the same degree of agreement exists with the experimental data.

4. SENSIBILITY TO CHANGE IN LOVIBOND NUMBER

(a) SENSIBILITY TO CHANGE IN LOVIBOND YELLOW

Analogous to equation 10 the circle construction yields:

$$\frac{dN''}{dE}=\frac{\sqrt{6}KdN''}{2\sqrt{(dr)^2+(dg)^2+(db)^2}} \tag{10a}$$

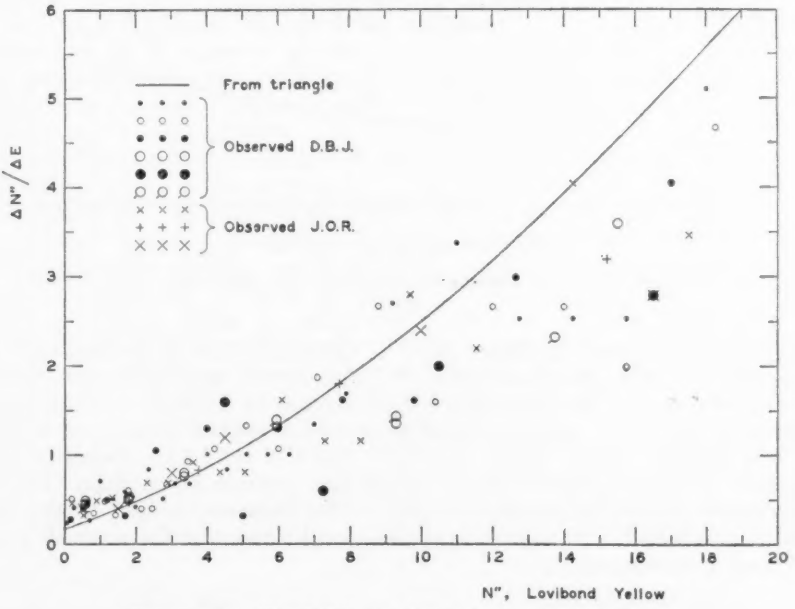

FIGURE 9.—*Sensibility to change in Lovibond yellow.*

where N'' refers to Lovibond-yellow number on the Priest-Gibson scale,[29] and *dr*, *dg*, *db* refer to differences along the Lovibond-yellow locus.

[29] I. G. Priest and K. S. Gibson, *Standardizing the red and yellow Lovibond glasses.* J. Opt. Soc. Am. and Rev. Sci. Inst. **16,** 116 (1928).

In figure 9 are shown experimental determinations of this quantity[30] previously reported as dp/dE on the somewhat inaccurate assumption that the dominant wave length for the Lovibond yellow glasses is constant. The curve represents the right-hand member of equation 10a with K taken as 0.0045. It is seen that the agreement is fair.

(b) SENSIBILITY TO CHANGE IN LOVIBOND RED COMBINED WITH 35 YELLOW

Equation 10a applies to this case also if N'' is taken to refer to Lovibond-red number on the Priest-Gibson scale [31] combined with 35 yellow, and if dr, dg, db refer to differences along the Lovibond $35Y+N''R$ locus.

In figure 10 are shown some rather inaccurate determinations of this quantity by way of the probable error of a single setting for

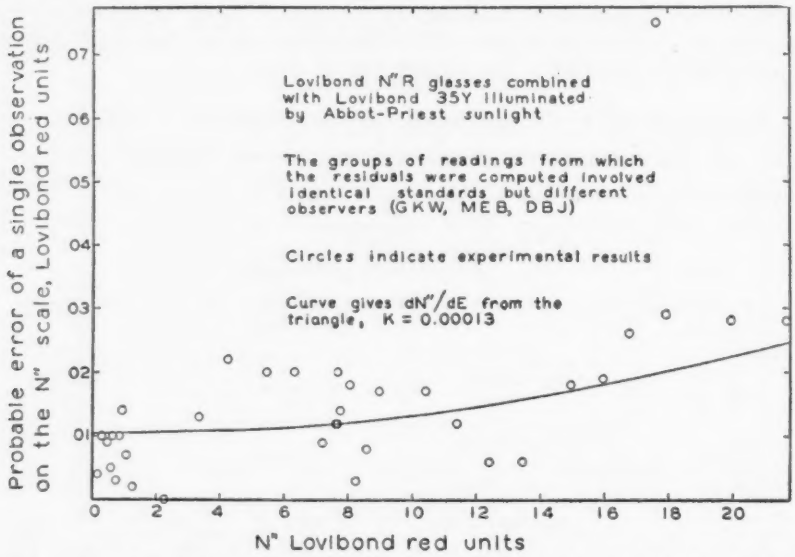

FIGURE 10.—*Sensibility to change in Lovibond red combined with Lovibond 35 yellow.*

chromaticity match in terms of N''. These data were presented and discussed in the previous paper.[32] The curve represents the right-hand member of equation 10a with K taken as 0.00013. The agreement is seen to be about as good as can be expected from data of this low precision (note point at 0.075 for $N''=17.7$). Possibly the circles indicate a curve with a somewhat greater slope than that of the curve derived from the triangle. The decrease in field brightness that accompanies an increase in N'' would account for a small part of such a discrepancy.

[30] J. Opt. Soc. Am. **23**, 35 (1933).
[31] K. S. Gibson and G. W. Haupt, *Standardization of Lovibond red glasses in combination with Lovibond 35 yellow*. J. Research NBS **13**, 433 (1934) RP718.
[32] J. Opt. Soc. Am. **22**, 98 (1932).

5. CONCLUSIONS FROM THE COMPARISONS

In every case the agreement previously obtained has been equaled or bettered, and in one case it has been notably improved. (See fig. 6.) Agreement with data appearing since the previous paper has also been satisfactory. Considering the rather large individual-observer variation it is estimated that the uniform-chromaticity-scale triangle represents about nine-tenths of available data on chromaticity sensibility within their experimental uncertainty.

V. APPLICATIONS OF THE TRIANGLE

The data presented indicate that the system chosen yields, as intended, a Maxwell triangle on which to a good approximation the length of a line is proportional to the chromaticity difference between the stimuli represented at its extremes. Although the data examined nearly all referred to small differences it is probable that the approximation is of the same order for large differences.[33] The degree of approximation, while by no means sufficient to disprove Schrödinger's [34] theoretical conclusion that such a representation should be made on a spherical surface, is close enough to be of some theoretical interest. Since the coordinate system chosen is only one of an infinity of systems each having the same essential property, it appears possible to fit with certain restrictions the uniform-chromaticity-scale triangle to many of the theories of vision, such as the Hering opponent-colors theory, the Young-Helmholtz three-components formulation, Hecht's [35] modification of it, or the level theory of G. E. Müller.[36] In this way the implications of the uniform-scale triangle might find expression in a variety of theoretical terms. Possibly, too, the theoretical formulation which is found to accommodate the uniform-scale triangle most conveniently may be thought to have some advantage over the others.

Two practical applications of the triangle may be pointed out. One obvious use is the estimation of the chromaticity difference between any two stimuli from their tristimulus specifications. To accomplish this with maximum accuracy the tristimulus specifications must be transformed by appropriate equations such as equations 3 or 3a. However, the mixture diagram of the standard 1931 ICI coordinate system might be made use of directly to find approximate values of chromaticity difference provided some means were available to take into account the distortion between the two diagrams. A convenient way to do this is to cover the uniform-scale triangle with a number of (say 30) equal circles; then transform by equation 3 these circles to the 1931 ICI mixture diagram where they will appear as ellipses. The expansion or contraction of the various parts of the diagram relative to corresponding parts of the uniform-scale diagram would be indicated by the sizes, eccentricities, and orientations of these ellipses.

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[33] J. Opt. Soc. Am. **23,** 35 (1933).
[34] E. Schrödinger, *Grundlinien einer Theorie der Farbenmetrik im Tagessehen.* Ann. d. Physik [4], **63,** 481 (1920); Die Gesichtsempfindungen, Müller-Pouillets Lehrbuch der Physik, 2d ed., **2,** 552 (1926).
[35] Selig Hecht, *The interrelation of various aspects of color vision.* J. Opt. Soc. Am. **21,** 615 (1931).
[36] G. E. Müller, Über die Farbenempfindungen. Leipzig: Barth (1930).

Perhaps the most important practical application of the uniform-scale triangle is its use in finding from any series of colors the one most resembling any neighboring color of the same brilliance. The method, of course, is to draw the shortest line from the locus of the series to the point representing the neighboring color. This is the geometric equivalent of the method of observation on which many plans of color grading are based. The characteristic of these plans is that they pay attention to chromaticity differences along a series of color standards, and in the usual case that no member of the series gives a perfect chromaticity match, the nearest match is set and the residual difference neglected. In this way a problem which, strictly, is two-dimensional finds a one-dimensional solution that is close enough to be of practical use.

Examples of this plan are the color-grading of illuminants according to the color temperature,[37] the grading of cottonseed oil according to Lovibond red number combined with Lovibond 35 yellow,[38] and the grading of lubricating oil according to the standards of the well-known Union colorimeter.[39] Many uses of a color comparator (such as the Duboscq) having for comparison a column of liquid of variable height are more or less allied to this plan of color grading; those involving a column producing a relatively large brightness change are little allied, but those involving chiefly changes in chromaticity are good examples of this plan.

In finding nearest color from a series the uniform-scale triangle may be used directly. The locus of the series is plotted together with the point representing the neighboring chromaticity, and the normal to the locus through the point gives the nearest chromaticity of the series. This necessitates transforming the tristimulus specification of the given chromaticity to the uniform-scale triangle each time. It is also possible to carry out the operation once for all by drawing on the uniform-scale triangle a large number of normals to the locus of the series completely covering at sufficiently small intervals the areas of the triangle near the locus. These normals could then be transformed by equation 3 to the standard 1931 ICI coordinate system and they would permit nearest chromaticity to be found from trilinear coordinates in the standard system without the necessity for transformation each time to the uniform-scale triangle. It is planned to do this for the Planckian locus to facilitate finding nearest color temperature. Preliminary comparison of nearest color temperatures found by the uniform-scale triangle indicates good agreement with those found by Davis' empirical method.[40]

[37] I. G. Priest, *The complete scale of color temperature* * * *. Phys. Rev. [2], **20**, 93 (1922); *The colorimetry and photometry of daylight and incandescent illuminants* * * *, J. Opt. Soc. Am. and Rev. Sci. Inst., **7**, 1175 (1923).

[38] *Report of Color Committee of the American Oil Chemists' Society*, 1932–1933. Oil and Soap, **10**, 114 (1933).

[39] In this instrument no provision at all is made for equalizing the brightnesses of the two fields; hence, the problem, strictly a tridimensional one, is reduced to a single specification by neglecting both small chromaticity and small brilliance differences.

[40] R. Davis, *A correlated color temperature for illuminants*. BS J. Research, **7**, 659 (1931) RP 365.

VI. SUMMARY

The uniform-chromaticity-scale triangle is shown to be in good agreement with a large proportion of published data on chromaticity sensibility. The scope, reliability, and consistency of these data are such that it is planned to use the triangle for estimation of chromaticity differences and for the determination of nearest chromaticity from a series for any neighboring chromaticity.

VII. APPENDIX

If it be desired to avoid the use of triangular coordinate plots, the trilinear coordinates, r, g, b, may be plotted in rectangular coordinates by the transformation:

$$\begin{aligned} x&=(2b+g)/\sqrt{3} \\ y&=g \end{aligned} \tag{11}$$

where x and y are abscissa and ordinate, respectively, of the usual rectangular coordinates.[41] These transformations place the equilateral triangle (see fig. 1) in the first quadrant of the (x, y)-plot, with the G-point ($r=0$, $g=1$, $b=0$) uppermost and the R-point ($r=1$, $g=b=0$) at the origin ($x=y=0$).

In rectangular coordinates eq 2 may be written in the familiar form:

$$D=\sqrt{(\Delta x)^2+(\Delta y)^2} \tag{12}$$

and eq 2a becomes:

$$D=\begin{cases}\Delta x\sqrt{(\Delta y/\Delta x)^2+1}, \text{ or} \\ \Delta y\sqrt{(\Delta x/\Delta y)^2+1}\end{cases} \tag{12a}$$

WASHINGTON, November 9, 1934.

[41] Note distinction from $\bar{x}$ and $\bar{y}$ of eq 3.

U. S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP757

Part of Journal of Research of the National Bureau of Standards, Volume 14, January 1935

USE OF THE PIPETTE METHOD IN THE FINENESS TEST OF MOLDING SAND

By Clarence E. Jackson and C. M. Saeger, Jr.

ABSTRACT

The fineness, or the size distribution, of the constituent particles of a material is an important factor in determining many of the physical characteristics. No great difficulty is encountered in sizing the larger particles by the use of sieves, but for particles finer than 50 microns in diameter other methods must be employed. The pipette method has been satisfactorily used in analysis of particle sizes of soils. Details of the development and use of the pipette method in the fineness test of molding sands are outlined in this paper. The method of computation and scope of results are shown by typical examples. A rapid method suitable for foundry control work and routine testing is suggested.

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I. INTRODUCTION

The determination of fineness is one of the most important tests made on a molding sand. The permeability, strength, refractoriness, and moisture required for tempering the sand, as well as the surface finish obtained on castings made in the sand, to a large degree depend upon the size distribution of the constituent particles. In the present method for classification adopted as a standard by the American Foundrymen's Association[1] the particles of a molding sand are classed in two groups by means of a sedimentation method, the larger particles being termed "grain material", and the smaller particles, "clay substance." A sample of molding sand is dispersed in distilled water and allowed to settle. Clay substance is the portion which settles at a rate less than 1 in./min. The faster settling material constitutes the grain and is further classified by a series of sieves, the finest being a no. 270 sieve. The portion of the grain which passes through a no.

[1] Testing and Grading Foundry Sands, Standards and Tentative Standards. Fineness Test. p. 86. American Foundrymen's Association, Chicago.

270 sieve and still settles at a rate faster than 1 in./min. in distilled water, is called "pan material" or "silt".

In view of recent developments in the methods [2 3 4 5 6 7] for measurement of subsieve particle sizes, it was felt that improvement in the method for sizing the particles of molding sands was desirable. After a preliminary study of the available methods, the pipette method was selected as being the most suitable for this particular use.

II. THE PIPETTE METHOD

The pipette method was developed independently by Robinson in Wales [8], Krauss in Germany [9], and Jennings, Thomas, and Gardner [10] in the United States. It is used in soil analysis by the Bureau of Chemistry and Soils of the U. S. Department of Agriculture and is readily adaptable to the analysis of molding sands. An advantage of this method is that determinations of many size classes can be easily performed on one sample.

The pipette method of determining size classes depends on the relation of the size of a particle to its velocity when allowed to settle freely in a suitable medium. The relation between size and rate of fall of solid spherical particles in any liquid is given by the following form of Stokes' equation [11]:

$$t=\left\{\frac{18\,H\,u}{(P_1-P_2)gd^2}\right\}10^8$$

Where t=time of settling in seconds.
H=depth of settling in centimeters.
u=viscosity of dispersing medium in poises.
P_1=density of particles in g/cm^3.
P_2=density of dispersing medium in g/cm^3.
g=acceleration of gravity, 980 cm/sec/sec.
d=diameter of particles in microns ($1\,\mu$=0.001 mm).

This equation although subject to certain limitations [12] has been used in the grading by sedimentation methods of molding sand or other particles of irregular shape. This application involves the assumption that the effective diameter of an irregular particle is the same as the diameter of a solid spherical particle which settles at the same rate. A classification of irregular particles, according to Stokes'

[2] H. G. Schurecht, *Elutriation tests on American kaolins*, J. Am. Ceram. Soc. **3**, 355 (1920).
[3] H. G. Schurecht, *Sedimentation as a means of classifying extremely fine particles*. J. Am. Ceram. Soc. **4**, 812 (1921).
[4] L. A. Wagner, *A rapid method for the determination of the specific surface of Portland cement*. Proc. Am. Soc. Testing Mats. **33**, part II, 553 (1933).
[5] R. C. Thoreen, *Comments on the hydrometer method of mechanical analysis*. Public Roads **14**, 93 (1933).
[6] L. B. Olmstead, L. T. Alexander, and H. E. Middleton. *A pipette method of mechanical analysis of soils based on improved dispersion procedure*. U. S. Department of Agriculture, Washington, Tech. Bul. 170 (1930).
[7] W. C. A. Krumbein, *History of the principles and methods of mechanical analysis*, J. Sedimentary Petrology **2**, 89 (1932).
[8] J. Agr. Sci. **12**, 306 (1922).
[9] Intern. Mitt. z. Bodenkunde **13**, 147 (1923).
[10] Soil. Sci. **14**, 485 (1922).
[11] Cambridge Phil. Soc. Trans. **9**, 8 (1851–56).
[12] B. A. Keen, The Physical Properties of the Soil, chapter II, Mechanical Analysis, p. 37. Longmans, Green & Co. (1931).

equation is therefore on the basis of effective diameter rather than actual dimensions.

The principle of the pipette method is as follows: If solid particles suspended in a liquid are allowed to settle freely, then, in accordance with Stokes' equation, after a selected time interval, t, all the particles larger than diameter, d, will have fallen below a level designated as M (fig. 1). A layer at M will be free from large particles, whose velocity of fall exceeds H/t, but will contain all particles having less velocity in the same concentration as in the original suspension.[13] By means of a pipette whose tip is immersed to level M, a sample of the suspension may be obtained which will contain only particles smaller than diameter d. A choice of time and level to effect a separation at any desired diameter, can be made from Stokes' equation.

It is thus possible to separate the suspended material into 2 grades, coarse and fine, by means of a single pipette sample or to separate further and classify the material by means of additional pipette samples taken at selected intervals of time. In this investigation an effective diameter of 20μ was adopted as the dividing size between coarse material (grain) and fine material (clay substance) of molding sand. This distinction between grain material and clay substance is in agreement with the American Foundrymen's Association procedure.[14]

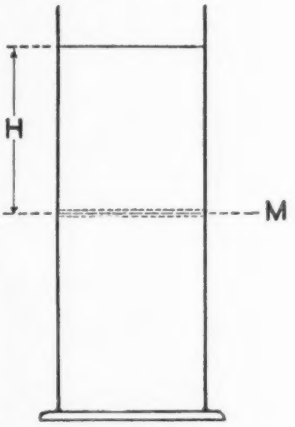

FIGURE 1.—*Diagram for explanation of principle of pipette method.*

A nomograph, based on Stokes' equation, shown in figure 2, furnishes a convenient means for determining the interrelation of temperature, particle diameter of molding sand, and time of settling to an arbitrary selected depth of 5 inches in distilled water. Data on viscosity of distilled water were taken from the work of Jackson and Bingham;[15] the density of molding sand (2.65) was taken from the work of Searle[16] on siliceous materials. A straight line across the 3 branches of the nomograph indicates the interrelation of temperature, particle diameter, and time of settling; for example, the broken line in figure 2 shows that after 5 minutes' settling at 27° C the suspension 5 inches below the surface will be free from all particles larger than 20μ in effective diameter.

[13] For an analysis of the fall of particles from a suspension see M. Kohn, *Particle size determination by means of pipette analysis* Tonindustrie Zeitung **531,** 730 (1927).
[14] Testing and Grading Foundry Sands, Standards and Tentative Standards. Fineness Test, p. 86. American Foundryman's Association, Chicago.
[15] Bul. BS 14, 59 (1918) S298.
[16] Chemistry and Physics of Clays, p. 218. Ernest Benn, Limited, London (1924).

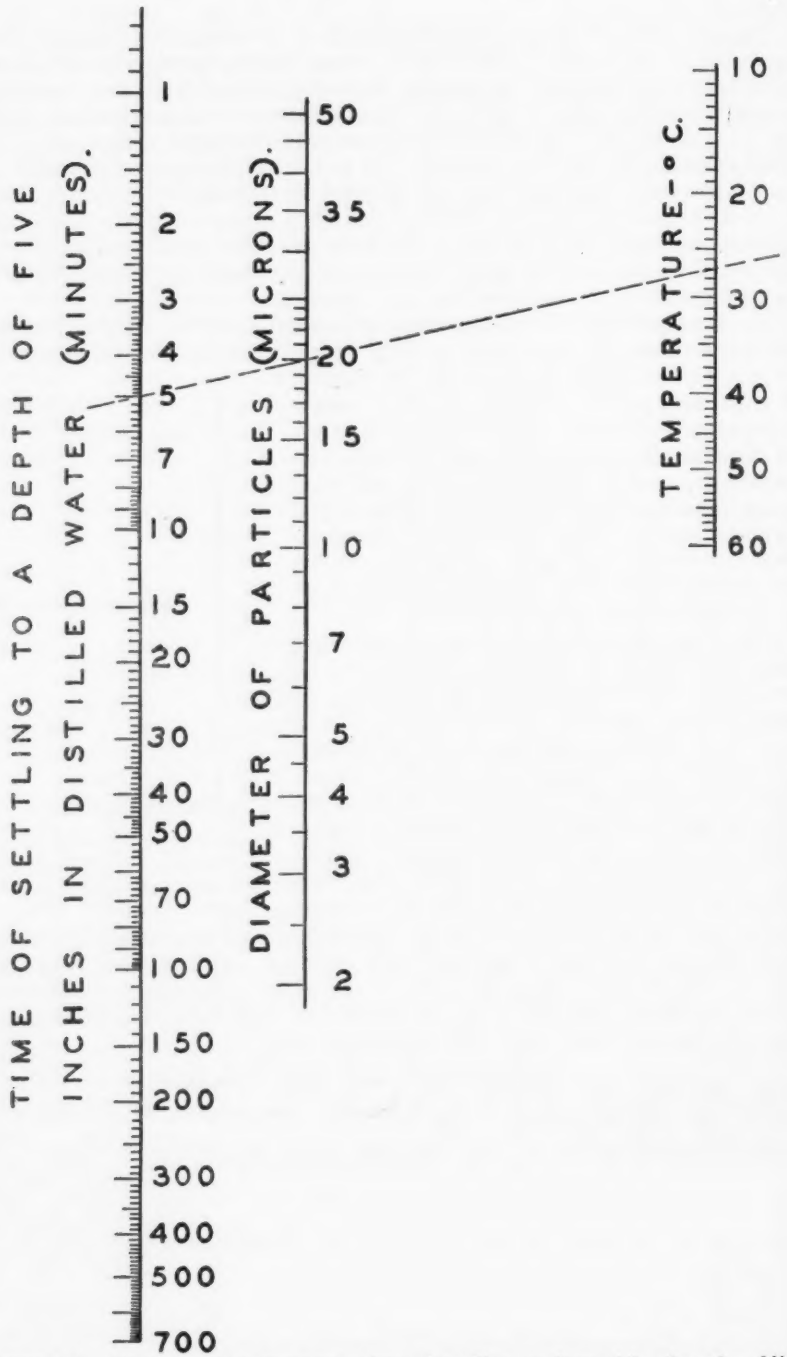

FIGURE 2.—*Relation of temperature, time of settling, and particle size of molding sand.*

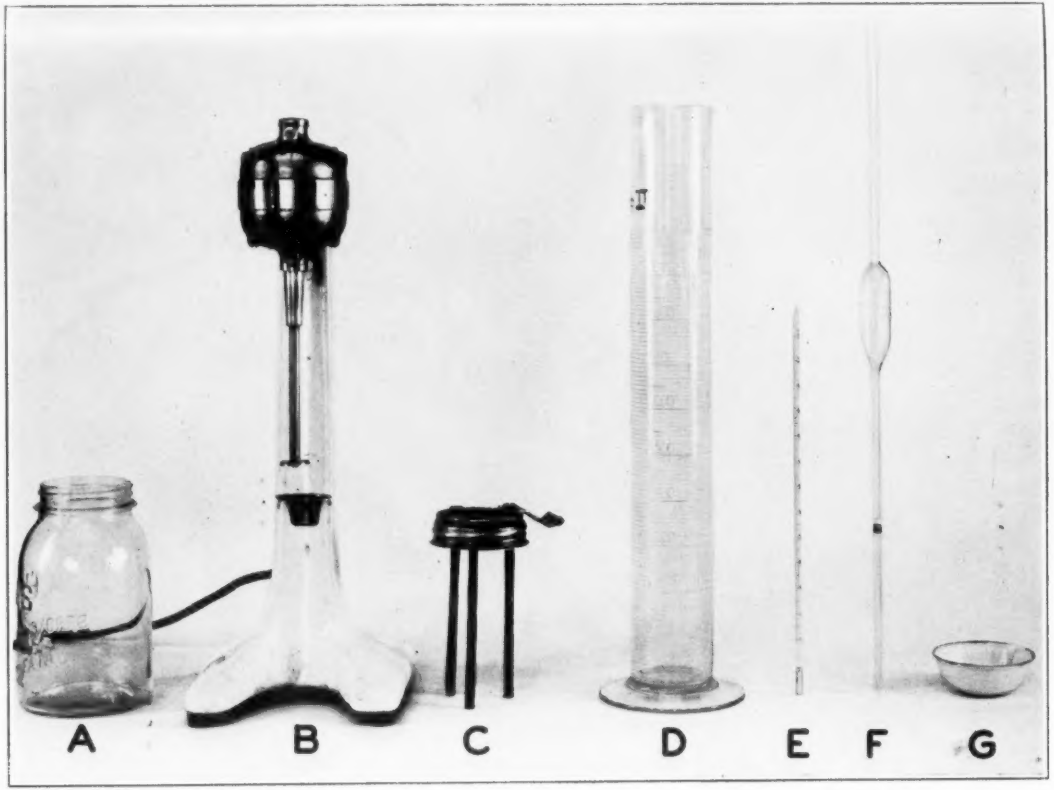

FIGURE 3.—*Apparatus used in the pipette method of testing the fineness of molding sand.*

A, Quart fruit jar; B, milk-shake stirrer; C, baffle system; D, 1,000-ml graduated cylinder; E, thermometer; F, transfer pipette; G, evaporating dish, 3-in. diameter.

III. DETAILS OF PROCEDURE

A suspension of the molding sand for the pipette method is prepared as follows: A 50-g sample is placed in a glass jar (1-quart capacity) with a screw top, covered with 475 ml of distilled water, and 25 ml of a 1 percent aqueous solution of sodium hydroxide is added to deflocculate the clay. The sand is dispersed for a period of 5 minutes in the 500 ml of solution by means of a small electrically operated stirrer. Baffles, consisting of 3 pieces of brass rod (3/16-inch diameter) projecting perpendicularly from a brass ring held in place at the top of the jar by the jar cap, hasten the process of dispersion. Snugly fitting rubber tubing on the baffle rods prevents excessive break-up of the grain material. The arrangement of these baffle rods is shown in figure 3, together with other equipment used in the dispersion of the sample, and in the sampling and analysis by the pipette method. The dispersed suspension together with the rinsings of the jar are transferred to a graduated cylinder of 1-liter capacity and distilled water is added to bring the volume up to 1 liter. After closing the open end of the cylinder, it is inverted and agitated for a period of 1 minute to insure uniform mixing of the original dispersion and the added water. The graduated cylinder is then set upright; a stop watch is started, signifying the beginning of actual settling. The temperature of the suspension, observed by means of a thermometer determines, from the nomograph (fig. 2), the time of settling of the suspension.

About 10 seconds before the indicated time has elapsed a 25-ml pipette, the volume of which has been accurately determined, is inserted into the suspension until the tip is 5 inches below the surface. When the time limit is reached, the pipette is filled rapidly (in less than 30 seconds). The contents are transferred to a weighed porcelain evaporating dish; the pipette is rinsed with distilled water and the rinsings added to the sample in the evaporating dish. After evaporating to dryness at a temperature of 105 to 110° C, preferably in an oven, the dish is allowed to cool in a desiccator and is then reweighed.[17] A balance accurate to 1 mg should be used. The pipette is thorougly cleaned and dried after each sampling by rinsing with alcohol and ether. Sampling may be repeated at progressive intervals to obtain additional size separations. Duplicate determinations may be obtained after reagitation of the remaining suspension. For routine work, duplicate pipette samples are taken representing a separation at 20 μ.

The weight of the dried sample in the evaporating dish must be corrected for the small amount of sodium hydroxide which is present. Twenty-five ml of a 1-percent solution of sodium hydroxide, equivalent to 0.25 g of sodium hydroxide, was present in the 500 ml of solution which was diluted to 1,000 ml. Each 25-ml sample of the diluted solution therefore contains $0.025 \times 0.25 = 0.006$ g of sodium hydroxide. This weight must be subtracted from the weight of the dried material which was obtained from a pipette sample of the suspension.

[17] For foundry control work and routine testing for clay substance a complete determination may be made in approximately 30 minutes by carefully evaporating the pipette portion in a weighed 250 ml heat-resisting glass beaker over a low gas flame, cooling and reweighing. This weight affords a basis for the clay substance calculation.

To obtain the size distribution of the grain material of the sample the remaining suspension is emptied on a wet no. 270 sieve and washed by a gentle stream of water which carries most of the fine particles through the sieve. The sieve containing the coarser grain is dried for ½ hour in an oven at a temperature of 105 to 110 ° C. After cooling, the dried grain material is weighed and is classified by means of sieves according to the regular American Foundrymen's Association practice.[18] This indicates the size distribution of the coarser material, from the particles of largest diameter down to the smallest particles retained on a no. 270 sieve. Since the no. 270 sieve has a nominal opening of 0.053 mm, particles having a diameter of approximately 50 μ or less will pass through this sieve.[19] Analysis of the pipette sample, as already described, determines the amount of clay substance finer than 20 μ. The material between 50 and 20 μ in size, called "pan material" or "silt", is determined as the difference between the original weight of the sample and the combined weights of the material greater than 50 μ and less than 20 μ.

IV. RESULTS OBTAINED BY THE PIPETTE METHOD

The following data and computations illustrate the information obtained from a fineness analysis of a 50-g sample of fine brass molding sand.

Determination of clay substance (material less than 20μ in diameter):

Temperature	° C	27
Time of settling	min	5
Volume of pipette	ml	25.11
Dry weight of clay substance and sodium hydroxide in pipette portion	g	.150
Weight of sodium hydroxide in pipette portion	do	.006
Net weight of clay substance in pipette sample	do	.144
Total weight of clay substance in 1000 ml of original suspension (0.144×1000/25.11)	g	5.73
Weight percent of clay substance in terms of weight of original sample (5.73×100/50)	percent	11.46

Determination of grain material (material retained on no. 270 sieve):

Total weight of dry grain retained on no. 270 sieve, 26.72 g (53.4 percent).

This weight of dry grain is further classified by use of a series of sieves as shown in the summary of results.

Determination of pan material or silt (material passing a no. 270 sieve and larger than 20μ):

	Grams.
Weight of original sample	50
Combined weight of clay substance (5.73 g) and weight of grain coarser than no. 270 sieve (26.72 g)	32.45
Weight of silt, by difference	17.55

[18] Testing and Grading Foundry Sands, Standards and Tentative Standards. Fineness Test, p. 86. American Foundryman's Association, Chicago.

[19] In ordinary mechanical analyses of sand no attention is paid to absolute sizes of grains but the nominal sizes of the screen openings are taken as the sizes of separation. For further discussion the reader is referred to Techn. Pap. BS 48, 50 (1915) T48.

Summary of the results obtained for a sample of fine brass molding sand:

Retained on sieve no.:	*Percent*
6	0. 0
12	. 6
20	. 1
30	. 1
40	. 2
50	. 8
70	1. 4
100	3. 9
140	11. 2
200	23. 8
270	10. 8
Pan material or silt	35. 1
Clay substance	11. 46

Such a summary constitutes the conventional report of the fineness of a molding sand.

When further information is desired as to the size distribution of the fine portion of a sand, relative data suitable for comparison can be obtained by use of the pipette method. For example, the material finer than that retained on a no. 270 sieve in the above sample of fine brass molding sand showed the following size distribution:

		Percent
Material passing a no. 270 sieve		46. 6
Material with an effective diameter less than	35μ	16. 2
	20μ	11. 5
	10μ	9. 5
	5μ	7. 0

In order to establish the reproducibility of results obtained by the pipette method, 5 successive pipette samples for a 20μ separation were taken under similar conditions from a suspension of a sample of molding sand. The weights of the dry material less than 20μ in diameter, obtained from these 5 portions were 0.207, 0.209, 0.209, 0.207 and 0.206 g, which correspond to 16.5, 16.6, 16.6, 16.5, and 16.4 percent by weight, respectively.

V. SUMMARY

The pipette method is a modified sedimentation method for classifying finely divided material according to particle size. It is readily adaptable to the determination of the fineness of molding sand and has been satisfactorily used for this purpose at the National Bureau of Standards. The equipment required is easily assembled, the operation is simple, the time required for a determination is short, the information obtained is wider in scope, and the reproducibility of results is greater than is obtained by other methods now in use.

Washington, D. C., September 18, 1934.

U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

RESEARCH PAPER RP758

Part of Journal of Research of the National Bureau of Standards, Volume 14, January 1935

MOISTURE RELATIONS OF AIRCRAFT FABRICS

By Gordon M. Kline

ABSTRACT

The amount of moisture held at various relative humidities and the rate of absorption of this moisture have been determined for airplane and balloon cloths, airplane fabric doped with cellulose nitrate, outer-cover fabric doped with cellulose acetate, dope films, and gas-cell fabrics. The fabrics coated with cellulose nitrate dope show a maximum gain in weight in a saturated atmosphere of approximately 12 percent of their weight when in equilibrium with air at 21° C and 65 percent relative humidity. The fabrics coated with cellulose acetate dope behave similarly to the cellulose nitrate products at relative humidities as high as 97 percent; in a saturated atmosphere they are considerably more hygroscopic. Gas-cell fabric, which consisted of balloon cloth coated with a mixture of gelatin and rubber latex, containing polyglycerol as a plasticizer, is the most hygroscopic of the materials studied. On exposure to a saturated atmosphere lightweight gas-cell fabric takes up in 7 days water equivalent to approximately 50 percent of its weight, and in 4 weeks it approximately doubles its weight. Paraffin, which is always applied to the gas-cell fabric in service, retards considerably the rate of absorption; thus 14 percent by weight decreases the absorption of moisture to approximately 30 percent in 1 week and 60 percent in 4 weeks at 100 percent relative humidity. The deterioration of the gas-cell fabric by mold attack at high humidities has been found to take place very rapidly; it is recommended that a small amount of a fungicide be incorporated with the "gelatin-latex" coating to prevent this action.

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I. INTRODUCTION

Very few data are available in the literature relative to the amount of water held by airplane and airship fabrics at various relative humidities. W. G. Bird[1] presents the results of a few experiments with gas-cell fabric made with goldbeaters skin and doped (type unstated) outer cover cloth at 90 to 95 percent relative humidity and various temperatures. It was the purpose of this investigation to

[1] *The influence of atmospheric humidity and other factors upon the static lift of airships.* J. Roy. Aeron. Soc. 35, 973 (1931).

obtain data on the sensitivity of aircraft fabrics to humidity in order to ascertain the amount of water which the aircraft will be required to support under varying atmospheric conditions.

II. EXPERIMENTAL PROCEDURE

It was first attempted to determine the amount of moisture absorbed by balloon cloth at various humidities by the desiccator method described by McKee.[2] The method was found to be unsatisfactory because equilibrium conditions were disturbed when the lid of the desiccator was taken off to remove a sample for weighing. Frequently equilibrium was not restored in 24 hours. Furthermore considerable condensation of moisture on the samples and on the sides and tops of the desiccators took place at relative humidities above 90 percent, making accurate measurements of absorption of vapor impossible.

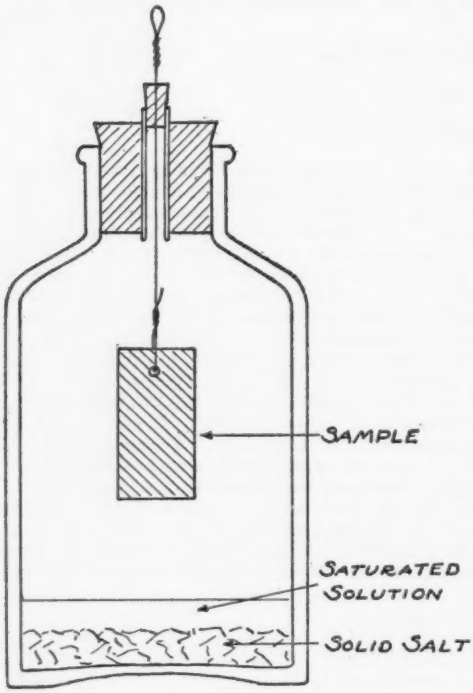

FIGURE 1.—*Diagram of apparatus used in measurement of absorption of moisture.*

The method described by Evans and Critchfield,[3] in which the sample is suspended on a wire through narrow glass tubing in the stopper of a 6-ounce bottle (fig. 1), was found to be satisfactory. The glass tube is closed between weighings by a paraffined cork through which the wire passes. The sample is weighed without removal from the bottle by supporting the bottle on a bridge over the balance pan and suspending the wire from the balance hook. Equilibrium conditions in the bottle are not noticeably disturbed during this weighing procedure. Condensation of moisture on the inner surfaces of the containers took place only at 100 percent relative humidity. No trouble was experienced even at this humidity with water dripping on the samples from above, as occurred when the desiccators were used. The reagents listed in table 1 were placed in the bottoms of the bottles to obtain the various humidities.[4] The solutions were agitated after each weighing to promote equilibrium conditions. These saturated salt solutions are much more satisfactory for obtaining various relative humidities than sulphuric-acid

[2] Paper Trade J. **97,** No. 6, 33 (Aug. 10, 1933).
[3] BS J. Research **11,** 147 (1933).
[4] International Critical Tables, first edition, McGraw-Hill Book Co., New York, **1,** 67 (1926).

solutions, since at constant temperature there is no change in concentration in the solution during the experiment and hence no change in the relative humidity above the solution as occurs when sulphuric acid is used. The bottles were placed in a constant temperature room which is kept at 21° C ± 1. All samples were conditioned at 65 percent relative humidity and 21° C ± 1 before being placed in the containers. The weights of the test pieces varied from 1 to 2.5 g (8 to 24 in.^{2}) depending upon the weight per unit area. The rate of change in weight at the various humidities was ascertained by weighing at suitable intervals until equilibrium was attained. The samples were weighed with a chemical balance and calibrated weights to the nearest tenth of a mg. The cork and wire, from which the sample was suspended, were weighed at the start and finish of each experiment and correction made on the equilibrium value only for any change in weight. The data given in the tables are the percentage changes in weight from the initial weight in the standard conditioning environment. For relative humidities below 65 percent the values are, therefore, negative.

TABLE 1.—*Reagents used to obtain various relative humidities*

Relative humidity	Reagent
Percent:	
0	Phosphorus pentoxide.
6	Saturated sodium hydroxide solution.
20	Saturated potassium acetate solution.
33	Saturated magnesium chloride solution.
55	Saturated calcium nitrate solution.
76	Saturated sodium chloride solution.
86	Saturated potassium chloride solution.
90	Saturated zinc sulphate solution.
94	Saturated potassium nitrate solution.
97	Saturated potassium sulphate solution.
100	Water.

An experimental method for determining the absorption of moisture was also used in which air at various relative humidities circulated about the sample. McKee [5] has described an apparatus for this purpose which is connected directly to a balance. It was found more convenient, however, to use the apparatus described below which permits the concurrent study of several samples. Air was passed through a series of 8 wide-mouthed bottles (one 22 ounces, four 12 ounces, one 6 ounces, two 12 ounces) fitted with 2-holed rubber stoppers and glass tubing; the bottles were interconnected by means of small pieces of rubber tubing over the ends of the glass tubing. The first bottle served as a trap. The next 3 contained the solution through which the air was bubbled to give the desired relative humidity. The temperature of the solution in the third bottle was found to be the same as the room temperature. Glass wool was added to the solutions to break up the bubbles and thereby promote the attainment of equilibrium conditions between vapor and solution. The fifth bottle contained only glass wool to trap any liquid particles carried with the air. The air at the desired relative humidity was then passed through the 6-ounce bottle con-

[5] Paper Trade J. 97, no. 6, 33 (Aug. 10, 1933).

taining the sample of aircraft fabric suspended from a wire passing through a third hole in the stopper. The seventh bottle served as a trap and the eighth bottle contained a small amount of the same solution that was present in the second, third, and fourth bottles. The speed with which the air passed through the system was readily estimated by the rate of formation of bubbles in the last bottle and was adjusted by means of stopcocks in the air line. The rate of passage of air was maintained at about 15 liters/hr. It was found advantageous to insert a 22-ounce bottle containing water and glass wool in the air line in order to approximately saturate the air before it reached the salt solutions. The excess moisture was removed by the salt solutions without difficulty, whereas less saturated air took up moisture from the solutions, causing the salt to crystallize in the glass tubing and stopping the flow of air. In order to weigh the sample it was only necessary to disconnect the bottle at the rubber tubing joints, stopper the glass tubing, place the bottle on the balance bridge, and hang the wire holding the sample on the balance hook.

Data are presented later in this paper which show that the moisture absorption is practically the same by both methods, moving air and static air. This indicates that the rate of diffusion of the water molecules to the neighborhood of the samples merely suspended over the salt solutions or water exceeded or was at least equal to the rate of absorption of the water vapor. The simplicity, reliability, and compactness of the static method make it the one to be preferred for most purposes. The data recorded in the tables were obtained by the static air method unless otherwise noted.

III. MOISTURE RELATIONS OF AIRCRAFT CLOTHS, DOPED FABRICS, AND DOPE FILMS AT VARIOUS RELATIVE HUMIDITIES

The equilibrium values for the moisture content of various aircraft cloths, fabrics coated with cellulose nitrate and cellulose acetate dopes, and dope films are presented in table 2. The change in weight of these materials up to and including 94 percent relative humidity is less than 10 percent of their weight in the conditioning atmosphere. The doped fabrics increase in weight by less than 10 percent at 97 percent relative humidity. At 100 percent relative humidity the cellulose acetate samples absorb more moisture than either the cellulose nitrate or cloth samples. This moisture, however, is taken up very slowly over long periods of time. Although the results obtained at 100 percent relative humidity are not as reliable as those at lower humidities, because of collection of moisture on the samples, the good agreement found for the 3 classes of materials, namely, cloth, cellulose acetate products, and cellulose nitrate products, indicates that the values are fairly reproducible. This has also been demonstrated with the gas-cell fabrics.

TABLE 2.—*Percentage change in weight of aircraft fabrics and dope films which have been conditioned in air at 21° C and 65 percent relative humidity when they are exposed at other relative humidities until equilibrium is reached*

Materials	Weight	Percentage change in weight at various relative humidities										
		At 0%	At 6%	At 20%	At 33%	At 55%	At 76%	At 86%	At 90%	At 94%	At 97%	At 100%
	oz/sq yd	%	%	%	%	%	%	%	%	%	%	%
Balloon cloth, unmercerized	2.11	−6.5	−4.7	−3.0	−2.3	−0.8	1.4	3.5	5.3	7.1	11.6	18.9
Airplane cloth, mercerized	4.13	−7.3	−5.1	−3.2	−2.2	−0.5	2.4	4.9	6.5	9.7	15.3	20.6
Airship outer cover, new cellulose acetate doped	5.90	−5.5	−4.5	−3.4	−2.9	−1.4	0.8	2.2	3.1	4.5	7.3	55.3
Airship outer cover, old cellulose acetate doped	6.12	−3.8	−2.8	------	−1.4	−0.5	0.8	1.9	2.6	4.0	9.4	39.5
Dope film, cellulose acetate	5.12	−2.6	−2.2	−1.8	−1.4	−0.7	0.7	1.6	2.3	2.9	4.0	30.5
Airplane fabric, new cellulose nitrate doped	5.88	−5.9	−4.1	−2.7	−2.0	−0.6	1.1	2.8	3.9	5.5	8.6	11.2
Airplane fabric, old cellulose nitrate doped	8.89	−4.6	−3.3	−2.1	−1.5	−0.5	0.7	1.7	2.5	3.7	5.7	11.8
Dope film, cellulose nitrate	5.52	−1.0	−0.8	−0.6	−0.5	−0.2	0.2	0.5	0.6	0.7	1.0	7.7

The results obtained with the mercerized airplane cloth and the unmercerized balloon cloth are similar to the moisture relations found by Urquhart[6] and his colleagues for mercerized yarn and raw cotton (fig. 2). It should be pointed out, however, that the latter investigators started with products which had been dried over phosphorus pentoxide at room temperature in obtaining their data. Our data were calculated to the dry basis for comparison in figure 2 with Urquhart's results. It will be noted that the moisture contents of the mercerized materials are slightly greater than those of the unmercerized materials.

The results of the tests on outer cover fabric doped with cellulose acetate are shown in figure 3. The "old-doped" sample was taken from the U. S. Navy dirigible *Los Angeles;* the "freshly-doped" sample was obtained from the Goodyear-Zeppelin Corporation, Akron, Ohio. Very little difference in the moisture relations of the 2 samples was observed. The data obtained for airplane fabrics coated with cellulose nitrate are also plotted in figure 3. The curves are very similar to those of the cellulose acetate products except that there is no sharp rise at 100 percent relative humidity. It will be noted that the cellulose acetate film unsupported by cloth holds considerably more moisture at all humidities than the cellulose nitrate film. However, both films hold less moisture than the cotton cloth up to and including 97 percent relative humidity. At 100 percent relative humidity the cellulose acetate film takes up more water than the cotton cloth. This water is not all absorbed by the sample, however, as it can be seen collecting on the surface. Sheppard and Newsome[7] have observed that esterification of the hydroxyl groups of the cellulose molecule decreases the amount of water taken up. The fact that the moisture content of the cellulose acetate film exceeds that of the cotton cloth may be attributed to a difference in the wettability of the surfaces or to other materials present in the dope. Since we are interested in the behavior of these materials under atmospheric conditions in which the dewpoint is often reached, the amount of moisture

[6] J. Text. Inst. **15**, T138 (1924); **23**, T135 (1932).
[7] J. Phys. Chem. **33**, 1817 (1929).

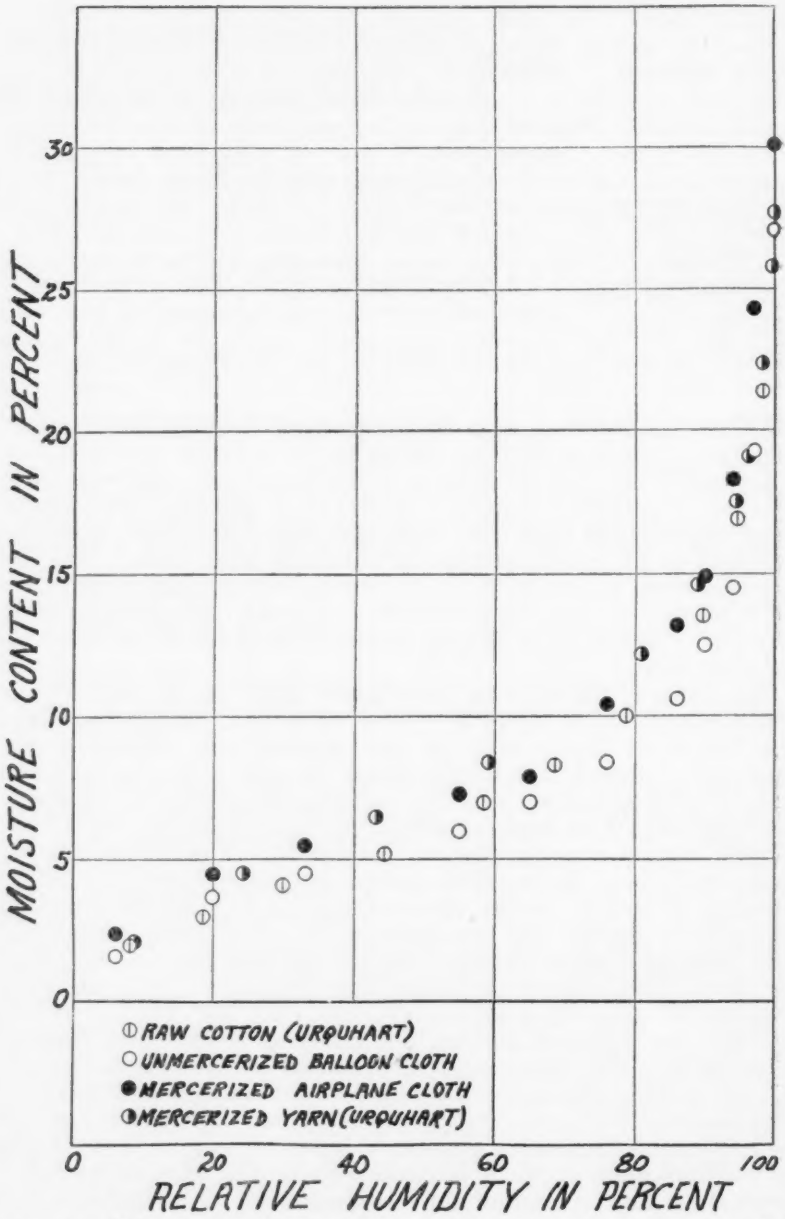

FIGURE 2.—*Moisture contents of raw cotton, cotton yarn, and aircraft cotton cloths at various relative humidities.*

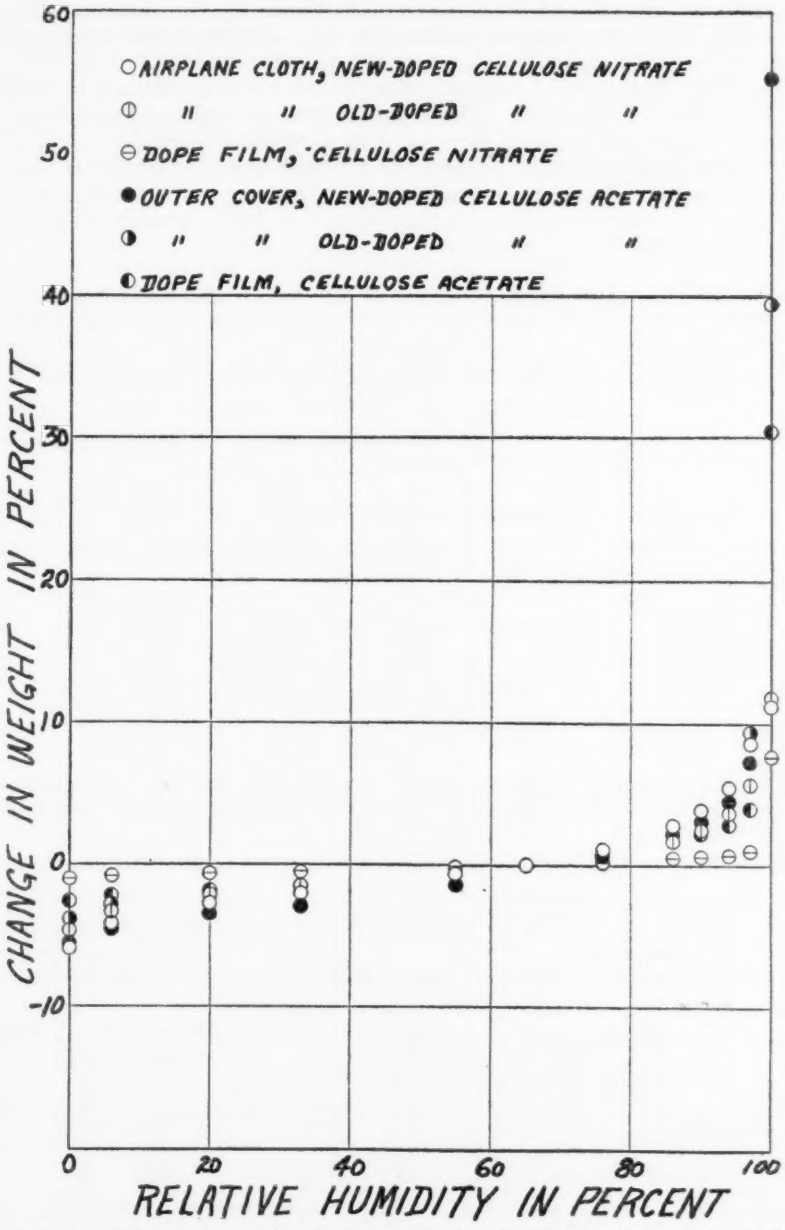

FIGURE 3.—*Changes in weight of fabrics coated with cellulose nitrate and cellulose acetate dopes and of dope films unsupported by cloth, which have been conditioned in air at 21° C and 65 percent relative humidity, when they are exposed at other relative humidities.*

which would be taken up by the material either by absorption or as a surface collection is of importance.

Data on the rate of absorption of moisture by the materials listed in table 2 are presented in tables 3 to 10. Approximate equilibrium conditions are reached in 24 hours for all samples exposed at relative humidities from 0 to 86 percent, after which time the change in weight is less than 0.5 percent. The same is true at relative humidities of 90 and 94 percent after 3 days, and at a relative humidity of 97 percent after 7 days, in which cases the average change thereafter is only 0.1 percent. The increase in weight of the various materials at 100 percent relative humidity on exposure for long periods of time is shown in table 11.

TABLE 3.—*Percentage change in weight of* HH *balloon cloth which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department specification 27C13; weight of fabric found to be 2.11 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−3.9	−4.7	−5.2	−6.0	−6.2	−6.3
6	−2.6	−3.9	−4.3	−4.5	−4.6	−4.6
20	−2.0	−2.6	−2.8	−2.9	−3.0	−3.0
33	−1.1	−1.7	−1.9	−2.0	−2.1	−2.1
55	−0.4	−0.5	−0.6	−0.6	−0.6	−0.7
76	0.5	0.8	0.9	1.2	1.4	1.5
86	1.1	1.9	2.6	3.3	3.5	3.6
90	1.8	3.2	4.1	5.4	5.4	5.3
94	1.9	3.5	4.7	6.6	7.1	7.3
97	2.8	4.7	6.1	9.2	10.7	11.3
100	3.3	5.3	7.0	10.9	14.0	15.8

TABLE 4.—*Percentage change in weight of airplane cloth which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department specification 27C12; weight of fabric found to be 4.13 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−3.5	−4.9	−5.7	−6.9	−7.2	−7.3
6	−2.7	−4.0	−4.6	−5.0	−5.1	−5.1
20	−1.8	−2.6	−2.9	−3.0	−3.1	−3.1
33	−1.2	−1.7	−1.9	−2.1	−2.1	−2.2
55	−0.3	−0.4	−0.4	−0.4	−0.5	−0.5
76	0.6	1.0	1.4	2.0	2.2	2.3
86	1.3	2.5	3.4	4.5	4.7	4.8
90	1.7	3.3	4.3	5.9	6.2	6.3
94	2.2	4.2	5.8	8.5	9.2	9.5
97	2.9	5.3	7.2	11.4	13.9	14.9
100	5.0	7.1	8.5	12.9	17.0	19.8

TABLE 5.—*Percentage change in weight of "freshly-doped" outer cover (cellulose acetate) which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to Goodyear-Zeppelin specification K-7204-A; weight of doped fabric found to be 5.90 oz/sq yd. Cloth corresponds to U. S. Navy Department specification 27C13a for BB type, weight 2.90 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−3.1	−4.2	−4.7	−5.2	−5.4	−5.5
6	−2.4	−3.5	−4.0	−4.3	−4.4	−4.4
20	−1.9	−2.7	−3.0	−3.2	−3.3	−3.3
33	−1.3	−2.0	−2.3	−2.5	−2.6	−2.7
55	−0.5	−0.7	−0.9	−0.9	−1.1	−1.2
76	0.3	0.6	0.6	0.8	0.7	0.5
86	0.8	1.4	1.8	2.2	2.0	1.8
90	1.1	1.9	2.5	3.1	3.0	2.8
94	1.4	2.5	3.4	4.5	4.4	4.3
97	1.4	3.0	4.2	6.4	7.1	7.3
100	3.2	4.7	6.0	8.7	12.1	15.7

TABLE 6.—*Percentage change in weight of "old-doped" outer cover (cellulose acetate) which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material taken from the *Los Angeles;* specification unknown; weight of doped fabric found to be 6.12 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−2.4	−3.1	−3.4	−3.7	−3.8	−3.8
6	−2.0	−2.5	−2.6	−2.7	−2.7	−2.7
33	−0.9	−1.2	−1.2	−1.3	−1.3	−1.3
55	−0.3	−0.4	−0.4	−0.4	−0.5	−0.5
76	0.3	0.5	0.6	0.7	0.7	0.8
86	0.8	1.3	1.5	1.7	1.8	1.9
90	1.0	1.5	1.9	2.3	2.4	2.5
94	1.5	2.2	2.7	3.6	3.8	4.0
97	1.9	3.0	3.9	6.2	8.5	9.5
100	2.4	3.7	4.9	9.2	15.5	23.4

TABLE 7.—*Percentage change in weight of cellulose acetate dope film which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department specification D-14 and thinner T-33; weight of film found to be 5.12 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods				
	1 hour	3 hours	6 hours	1 day	3 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−1.7	−2.2	−2.3	−2.4	−2.6
6	−1.6	−2.0	−2.1	−2.1	−2.2
20	−1.1	−1.5	−1.6	−1.7	−1.8
33	−0.8	−1.2	−1.2	−1.3	−1.4
55	−0.3	−0.5	−0.5	−0.6	−0.7
76	0.4	0.6	0.7	0.7	0.5
86	0.8	1.3	1.5	1.6	1.6
90	0.8	1.4	1.8	2.2	2.3
94	1.1	1.9	2.4	2.9	2.9
97	1.5	2.6	3.2	3.9	4.0
100	1.7	2.8	3.5	5.0	6.5

TABLE 8.—*Percentage change in weight of "freshly-doped" airplane fabric (cellulose nitrate) which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department Specifications 27C12a for cloth, D-12 for dope and T-25 for thinner; 4 coats of clear dope only; weight of doped fabric found to be 5.88 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−3.3	−4.4	−4.9	−5.6	−5.8	−5.9
6	−2.5	−3.5	−3.9	−4.1	−4.2	−4.2
20	−1.5	−2.3	−2.5	−2.7	−2.8	−2.8
33	−1.1	−1.6	−1.7	−1.8	−1.9	−2.0
55	−.4	−.5	−.5	−.6	−.6	−.6
76	.3	.5	.6	.8	1.0	1.0
86	.9	1.5	2.0	2.6	2.7	2.8
90	1.1	2.0	2.6	3.5	3.7	3.8
94	1.4	2.6	3.5	4.8	5.2	5.4
97	2.3	3.6	4.5	6.7	7.8	8.4
100	2.7	3.9	4.9	7.6	9.5	10.7

TABLE 9.—*Percentage change in weight of "old-doped" airplane fabric (cellulose nitrate) which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department Specifications 27C12 for cloth and 52-D2 for dope; aluminum pigment in top coats; weight of doped fabric found to be 8.89 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods					
	1 hour	3 hours	6 hours	1 day	3 days	7 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−2.3	−3.2	−3.7	−4.3	−4.5	−4.6
6	−2.0	−2.7	−3.0	−3.2	−3.3	−3.3
20	−1.2	−1.7	−1.9	−2.1	−2.1	−2.1
33	−.8	−1.2	−1.3	−1.4	−1.5	−1.5
55	−.3	−.4	−.4	−.4	−.4	−.5
76	.3	.5	.5	.6	.7	.7
86	.6	1.0	1.3	1.6		
90	.7	1.3	1.6	2.1	2.3	2.4
94	1.0	1.7	2.3	3.2	3.5	3.6
97	1.2	2.3	3.0	4.6	5.4	5.8
100	1.9	2.9	3.8	5.9	8.1	10.8

TABLE 10.—*Percentage change in weight of cellulose nitrate dope film which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to U. S. Navy Department Specifications D-12 for dope and T-25 for thinner; weight of dope film found to be 5.52 oz/sq yd]

Relative humidity	Percentage change in weight on exposure for various periods				
	1 hour	3 hours	6 hours	1 day	2 days
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0	−0.69	−0.90	−0.95	−0.92	−0.90
6	−.59	−.77	−.81	−.77	−.74
20	−.45	−.60	−.61	−.58	−.54
33	−.34	−.46	−.47	−.45	−.44
55	−.13	−.16	−.16	−.12	−.09
76	.16	.23	.24	.24	.22
86	.28	.43	.48	.52	.53
90	.33	.48	.55	.59	.55
94	.44	.58	.65	.69	.66
97	.50	.75	.87	.99	1.00
100	.64	.96	1.10	1.44	1.64

TABLE 11.—*Percentage gain in weight at 100 percent relative humidity of various aircraft fabrics and dope films which have been conditioned in air at 21° C and 65 percent relative humidity*

Materials	Percentage change in weight on exposure for various periods											
	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks	9 weeks	10 weeks	16 weeks	18 weeks	24 weeks	25 weeks
	Per-cent	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*	*Per-cent*
Balloon cloth, unmercerized	15.8	18.3	18.6	19.2	19.3	19.2	-----	-----	-----	-----	-----	-----
Airplane cloth, mercerized	19.8	20.7	20.8	20.8	20.7	-----	-----	-----	-----	-----	-----	-----
Outer cover, freshly-doped cellulose acetate	15.7	20.8	24.2	-----	31.4	33.4	40.7	-----	-----	48.6	55.6	53.6
Outer cover, old-doped cellulose acetate	23.4	29.4	33.9	33.5	-----	35.9	39.8	38.3	-----	-----	-----	-----
Cellulose acetate dope film	10.6	13.8	16.5	18.7	21.6	24.8	26.6	-----	30.5	25.1	-----	17.2
Airplane fabric, freshly-doped cellulose nitrate	10.7	-----	11.3	11.5	11.4	11.4	-----	-----	-----	-----	-----	-----
Airplane fabric, old-doped cellulose nitrate	10.8	11.7	-----	11.5	11.9	11.8	-----	-----	-----	-----	-----	-----
Cellulose nitrate dope film	2.8	4.1	5.0	6.3	6.8	7.0	7.7	-----	-----	3.4	-----	-----

IV. MOISTURE RELATIONS OF GAS-CELL FABRICS AT VARIOUS RELATIVE HUMIDITIES

The gas-cell fabrics studied were unmercerized balloon cloth coated with plasticized gelatin-latex. The base cloth of the lightweight fabric weighs 2.80 oz/sq yd and the gelatin-latex coating 2.13 oz/sq yd, according to Goodyear-Zeppelin Corporation specification K–13328. The base cloth of the heavyweight material weighs 4.20 oz/sq yd and the gelatin-latex coating 2.13 oz/sq yd, according to Goodyear-Zeppelin Corporation specification K–13329. It is the practice to coat both surfaces of the gas cell with paraffin after assembly. The results of tests with unparaffined and paraffined gas-cell fabrics are presented in table 12 and figure 4. All increases in weight are based on the weight of gelatin-latex fabric without paraffin in order to make the data comparable. The values given are the maximum observed rather than equilibrium points, since at relative humidities of 94 percent and higher mold grew on all samples, which caused them to lose weight after 3 to 4 weeks. The mold becomes visible to the eye after approximately 10 days. In regard to the prevention of this mold attack on gas-cell fabric, the studies on mildew prevention on painted surfaces conducted by Gardner, Hart, and Sward [8] are particularly pertinent. Mercuric chloride, mercurophen, and phenyl mercury acetate proved most effective. If it is desired to avoid toxic mercury compounds because of the danger to workmen in mixing, spraying and other operations, some of the chemicals which are suggested for use are thymol, methylisopropylphenol, mercaptobenzothiazole, sodium orthophenylphenate, and guaiacol. It is hoped that a mold-proof gas-cell fabric will be available at a later date in order to better establish the equilibrium points at 97 and 100 percent relative humidities. The concordance of the results on the various samples at the other humidities is very good.

[8] Scientific Section Circulars, National Paint, Varnish, and Lacquer Association, Inc., Washington, D.C., nos. 442, 448, and 464.

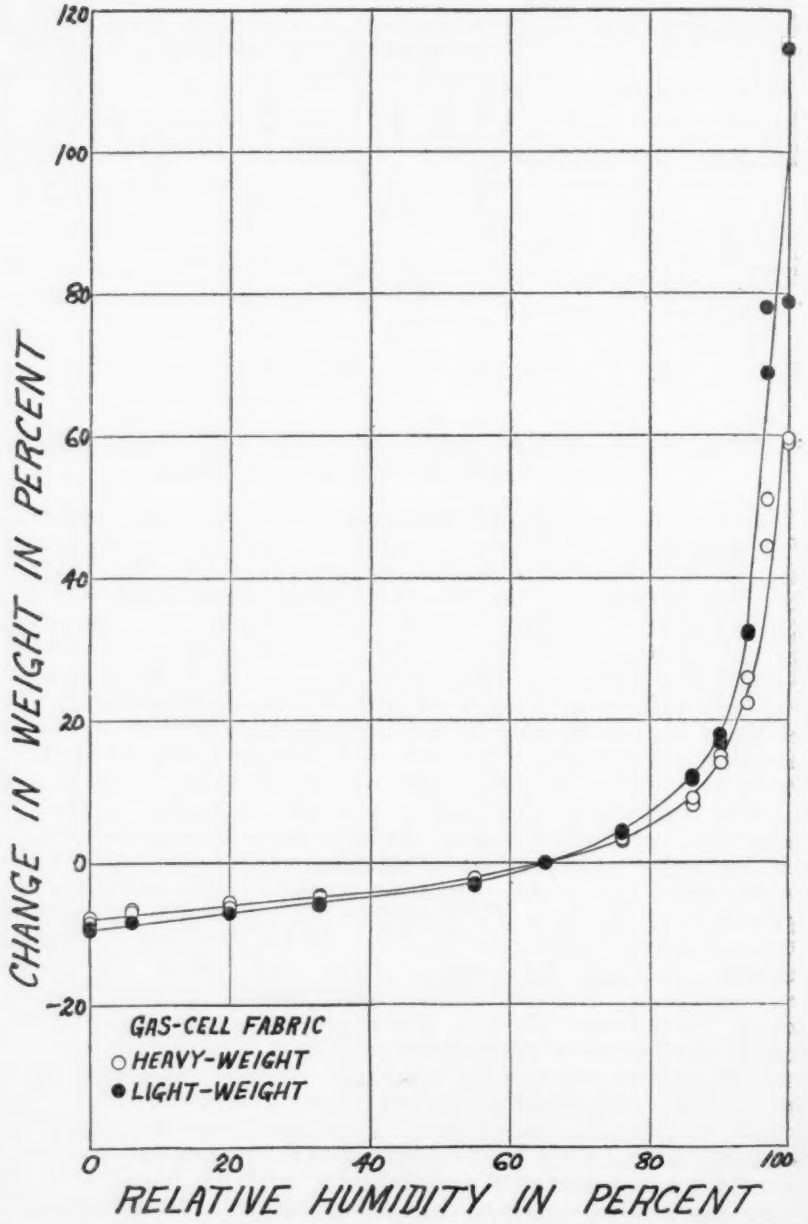

FIGURE 4.—*Change in weight of gas-cell fabrics which have been conditioned in air at 21° C and 65 percent relative humidity, when they are exposed at other relative humidities.*

TABLE 12.—*Change in weight of unparaffined and paraffined gas-cell fabrics which have been conditioned in air at 21° C and 65 percent relative humidity when they are exposed at other relative humidities*

[Materials correspond to Goodyear-Zeppelin Corporation specifications K-13328 (lightweight fabric) and K-13329 (heavyweight fabric)]

LIGHTWEIGHT FABRIC

Weight of paraffin	Total weight	Percentage change in weight at various relative humidities										
		At 0%	At 6%	At 20%	At 33%	At 55%	At 76%	At 86%	At 90%	At 94%	At 97%	At 100%
oz/sq yd	oz/sq yd	%	%	%	%	%	%	%	%	%	%	%
0.0	5.24	−9.1	−8.3	−7.0	−6.0	−3.0	4.2	11.5	17.8	32.2	68.9	79.0
0.0	4.93	−8.3						11.4		30.4	65.2	87.0
0.2	5.21	−9.4	−8.5	−7.0	−5.8	−2.9	4.4	11.6	16.7	32.0	78.2	114.6
0.7	5.63	−7.2						11.6		27.4	50.1	61.6
1.0	5.94	−8.5						12.1		29.7	56.6	79.9
HEAVYWEIGHT FABRIC												
0.0	6.35	−6.9						9.1		24.5	51.9	60.3
0.6	6.95	−7.8	−6.9	−5.6	−4.7	−2.2	3.4	9.4	14.0	25.8	51.0	58.9
0.8	7.03	−8.5	−6.6	−5.8	−4.9	−2.3	3.1	8.0	14.9	22.4	44.4	59.6

The increase in the moisture content of the samples at the high humidities is much greater for these gas-cell fabrics than for the other aircraft fabrics, listed in table 2. This is, of course, due to the gelatin and polyglycerol which are very hygroscopic. Bird[9] found that gas-cell fabric made with goldbeaters skin also takes up large amounts of water at high humidities. At 65° F and 90 to 95 percent relative humidity his sample increased in weight about 20 percent (dry basis) after 33 days, and when the conditions were changed to 75° F and 100 percent relative humidity it increased in weight about 60 percent and showed no sign of having reached a limit.

The rate of absorption of moisture by the lightweight and heavyweight gas-cell fabrics is shown in tables 13 and 14 for 86, 94, 97, and 100 percent relative humidities. The edges of the 2- by 8-inch pieces used for these tests were sealed with paraffin. The data in table 15 show that this treatment retards the moisture absorption quite appreciably at the high relative humidities for the paraffin-covered fabrics although the effect is rather slight on the unparaffined samples. It is evident from the data in tables 13 and 14 that the paraffin coating slows down the rate of absorption of moisture. However, several days are required even at these high humidities before the increase in weight due to the paraffin, namely, 14 and 20 percent, respectively, for the 2 lightweight paraffined fabrics and 9.5 percent for the heavyweight paraffined fabric, is counterbalanced by the lowered moisture absorption. It is also noteworthy that both paraffined and unparaffined samples reach the same equilibrium points at relative humidities up to and including 94 percent. At 97 and 100 percent relative humidities the retardation in rate of absorption of moisture because of the paraffin coating is not balanced by a similar inhibition of the attack by mold and an apparently lower total absorption of moisture is, therefore, obtained for these samples. In connection with this discussion of the effect of paraffin on the rate of absorption of

[9] J. Roy. Aero. Soc. **35**, 973 (1931).

moisture, it should be noted that Dunlap[10] has found that waxes are among the least efficient moisture-proofing materials when applied to wood. It is recognized that the paraffin also serves to overcome the inherent tackiness of the gelatin-latex gas-cell fabric and prevent it from adhering to itself. However, it is believed that a thorough study of moisture-proofing and tackiness-proofing coatings for gas-cell fabrics would lead to a more efficient material than paraffin for this purpose and might thereby effect a considerable saving in weight.

TABLE 13.—*Percentage change in weight of unparaffined and paraffined lightweight gelatin-latex fabric which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to Goodyear-Zeppelin specification K–13328; weight of unparaffined finished fabric found to be 4.93 oz/sq yd (fabric=2.80, gelatin-latex=2.13)]

Time (days)	Percentage change in weight at various relative humidities														
	At 0 percent, par. in oz/sq yd			At 86 percent, par. in oz/sq yd			At 94 percent, par. in oz/sq yd			At 97 percent, par. in oz/sq yd			At 100 percent, par. in oz/sq yd		
	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
¼4	−1.6	−0.4	−0.3	0.7	0.2	0.2	1.0	0.3	0.3	1.2	0.5	0.4	1.8	0.5	0.5
⅛	−3.7	− .9	− .8	1.7	.5	.4	2.6	.7	.7	2.9	1.1	.9	4.3	1.3	1.1
¼	−5.3	−1.7	−1.4	3.1	1.0	.8	4.5	1.4	1.3	5.0	2.1	1.6	7.1	2.3	2.0
1	−7.1	−4.2	−4.1	6.9	3.3	2.6	10.9	4.6	4.2	12.5	6.6	5.0	17.1	7.3	6.5
2	−7.4	−5.6	−6.0	9.2	5.2	4.5	15.6	7.5	7.3	18.9	10.8	8.7	24.6	12.4	11.2
3	−7.5	−6.2	−7.1	10.3	6.6	6.0	18.5	9.8	10.0	23.5	14.2	11.9	30.3	16.5	15.5
5	−7.6	−6.6	−7.9	11.1	8.4	7.8	22.2	13.4	13.5	30.5	20.1	16.5	40.0	23.5	21.6
7	−7.6	−6.8	−8.2	11.5	9.4	9.0	24.7	15.8	16.2	36.2	24.5	20.7	48.8	29.2	27.7
14	−7.7	−6.9	−8.5	11.5	10.9	11.2	28.1	21.4	22.2	48.5	36.1	32.2	71.1	45.0	46.4
21	−7.7	−7.0	−8.6	11.8	11.1	11.8	30.2	24.2	25.4	57.8	44.8	41.4	87.6	58.8	61.4
28	−7.7	−7.0	−8.6	11.7	11.3	11.9	29.9	25.9	27.2	62.9	49.9	49.1	95.7	62.3	74.0
35	−7.8	−7.0	−8.6	11.7	11.3	12.1	28.8	26.8	28.5	67.3	43.2	54.6	98.5	51.9	81.6
42	−7.8	−7.0	−8.7	11.6	11.3	12.2	28.2	26.6	28.8	69.9	47.4	53.6	91.2	53.4	64.2
70	−7.8	−7.0	−8.7	11.9	11.5	12.4	26.2	25.9	25.0	67.4	48.1	27.8	54.4	76.8	54.3

TABLE 14.—*Percentage change in weight of unparaffined and paraffined heavyweight gelatin-latex fabric which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to Goodyear-Zeppelin Corporation specification K–13329; weight of unparaffined finished fabric found to be 6.35 oz/sq yd (fabric=4.20, gelatin-latex=2.15); paraffined fabric contained 0.6 oz/sq yd paraffin]

Time (days)	Percentage change in weight at various relative humidities									
	At 0 percent		At 86 percent		At 94 percent		At 97 percent		At 100 percent	
	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
¼4	−1.2	−0.4	0.5	0.2	0.7	0.2	1.0	0.3	1.2	0.4
⅛	−2.8	−1.2	1.4	.5	1.8	.6	2.3	.8	2.9	1.0
¼	−4.3	−1.9	2.3	1.0	3.1	1.2	3.8	1.5	4.7	1.7
1	−6.2	−4.7	5.5	3.0	8.1	3.9	9.7	4.7	11.0	4.9
2	−6.5	−5.9	7.3	4.7	11.9	6.4	14.5	7.8	16.4	8.3
3	−6.6	−6.4	8.1	5.7	14.1	8.2	17.9	10.2	20.4	11.0
5	−6.7	−6.7	9.0	7.0	17.1	10.8	23.3	14.2	27.3	15.8
7	−6.7	−6.8	9.3	7.8	19.1	12.9	27.3	17.3	33.0	19.6
14	−6.7	−6.9	9.6	8.9	22.4	17.2	35.8	25.7	44.9	31.1
21	−6.7	−7.0	9.7	9.1	24.0	19.8	41.0	33.0	50.8	40.2
28	−6.7	−7.0	9.9	9.3	24.7	21.7	45.3	40.0	63.4	45.0
35	−6.7	−7.0	9.7	9.3	23.6	23.0	44.6	44.6	70.9	52.2
42	−6.8	−7.0	9.7	9.2	22.0	23.4	43.2	46.9	66.4	58.8
70	−6.8	−7.0	9.7	9.2	18.8	24.1	34.6	45.2	94.8	80.8

[10] Ind. Eng. Chem. **18**, 1230 (1926).

TABLE 15.—*Effect of edge sealing on the rate of absorption of moisture by unparaffined and paraffined lightweight gelatin-latex fabric which has been conditioned in air at 21° C and 65 percent relative humidity when it is exposed at other relative humidities*

[Material corresponds to Goodyear-Zeppelin Corporation specification K-13328; weight of unparaffined finished fabric found to be 4.93 oz/sq yd (fabric=2.80, gelatin-latex=2.13); paraffined fabric contained 1.0 oz/sq yd paraffin]

UNPARAFFINED FABRIC

Time	Percentage change in weight at various relative humidities									
	At 0 percent		At 86 percent		At 94 percent		At 97 percent		At 100 percent	
	Sealed	Open	Sealed	Open	Sealed	Open	Sealed	Open	Sealed	Open
Days	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	−7.1	−7.7	6.9	7.1	10.9	11.6	12.5	14.4	17.1	17.7
3	−7.5	−7.9	10.3	10.3	18.5	19.1	23.5	26.2	30.3	32.0
7	−7.6	−7.9	11.5	11.6	24.7	25.2	36.2	40.0	48.8	51.5
14	−7.7	−7.9	11.5	11.6	28.1	28.1	48.5	53.2	71.1	73.7
21	−7.7	−7.9	11.8	11.9	30.2	30.0	57.8	63.0	87.6	85.6
28	−7.7	−7.9	11.7	11.7	29.9	29.7	62.9	66.4	95.7	93.4
35	−7.8	−8.0	11.7	11.7	28.8	29.1	67.3	67.7	98.5	80.2

PARAFFINED FABRIC

1	−4.1	−4.7	2.6	3.1	4.2	5.4	5.0	7.3	6.5	10.1
3	−7.1	−7.6	6.0	6.5	10.0	11.8	11.9	16.3	15.5	21.4
7	−8.2	−8.4	9.0	9.5	16.2	18.1	20.7	27.2	27.7	36.9
14	−8.5	−8.6	11.2	11.4	22.2	24.1	32.2	40.4	46.4	55.3
21	−8.6	−8.6	11.8	11.9	25.4	26.9	41.1	45.4	61.4	57.8
28	−8.6	−8.6	11.9	12.0	27.2	28.1	49.1	46.4	74.0	59.1
35	−8.6	−8.6	12.1	12.1	28.5	28.2	54.6	45.1	81.6	58.3

The rate of loss of moisture taken up at the high humidities has also been investigated. After 7 days' exposure at the high humidities the edge-sealed samples were removed from the bottles and placed in the atmosphere of the room, kept at 65 percent relative humidity. The results in table 16 show that the moisture absorbed in 7 days by the unparaffined heavyweight fabrics is practically all lost at 65-percent relative humidity in 2 days, whereas the paraffined samples require about the same time for the desorption as for the absorption of the moisture. Similar results were obtained with lightweight gas-cell fabric.

A comparison of the use of static and flowing air of various relative humidities on the absorption of moisture by heavyweight gas-cell fabric is presented in table 17. It will be noted that there is practically no difference in the rate of absorption. The edges of the pieces used in this experiment were not sealed; thus there resulted a faster absorption of moisture than indicated for this material in tables 14 and 16. This would have served to emphasize any difference in rate due to the two methods of supplying moisture. Similar results were obtained with unparaffined lightweight gas-cell fabric.

TABLE 16.—*Absorption and desorption of moisture by unparaffined and paraffined heavyweight gelatin-latex fabric which has been conditioned in air at 21° C and 65 percent relative humidity*

[Material corresponds to Goodyear-Zeppelin Corporation specification K–13329; weight of unparaffined finished fabric found to be 6.35 oz/sq yd (fabric=4.20, gelatin-latex=2.15); paraffined fabric contained 0.6 oz/sq yd paraffin]

Time	Percentage change in weight at various relative humidities									
	At 0 percent		At 86 percent		At 94 percent		At 97 percent		At 100 percent	
	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.	Unpar.	Par.
Days	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
¼	−1.4	−0.4	0.6	0.2	0.7	0.2	0.9	0.4	1.3	0.4
⅛	−3.0	−1.0	1.4	0.5	1.9	0.6	2.3	0.9	3.0	1.1
¼	−4.4	−1.8	2.3	0.9	3.3	1.1	3.8	1.7	4.9	1.9
1	−6.2	−4.5	5.4	2.9	8.5	3.4	9.5	5.0	11.0	5.4
2	−6.5	−5.8	7.4	4.6	12.5	5.8	14.9	8.5	17.4	8.9
3	−6.6	−6.3	8.2	5.6	14.9	7.5	18.6	11.0	22.0	11.7
5	−6.7	−6.6	8.9	7.0	17.9	10.2	24.4	15.3	29.9	16.7
7	−6.7	−6.7	9.1	7.8	19.8	12.3	28.6	18.4	35.0	20.7
SAMPLES REEXPOSED TO 65 PERCENT RELATIVE HUMIDITY										
¼	1.6	0.3	−1.0	−0.3	−1.5	−0.3	−2.2	−0.6	−4.6	−1.0
⅛	3.3	0.9	−2.5	−0.7	−3.9	−0.7	−5.0	−1.4	−8.1	−2.0
¼	4.7	1.5	−4.2	−1.2	−7.0	−1.3	−8.5	−2.5	−12.2	−3.1
1	6.4	3.9	−7.9	−3.7	−16.1	−4.4	−21.6	−7.6	−27.6	−8.3
2	6.7	5.3	−8.7	−5.6	−18.9	−7.3	−27.3	−12.3	−34.5	−13.1
3	6.7	5.9	−8.7	−6.4	−19.3	−8.9	−28.1	−14.8	−35.4	−15.9
5	6.7	6.5	−8.8	−7.1	−19.4	−10.7	−28.4	−17.0	−35.6	−18.8
7	6.7	6.6	−8.9	−7.4	−19.5	−11.5	−28.5	−17.8	−35.7	−20.0

TABLE 17.—*Comparison of the effects of static and flowing air of various relative humidities on the change in weight of heavyweight gelatin-latex fabric which has been conditioned in air at 21° C and 65 percent relative humidity*

[Material corresponds to Goodyear-Zeppelin Corporation specification K–13329; weight of finished fabric found to be 6.95 oz/sq yd (fabric=4.20, gelatin-latex=2.15, paraffin=0.60)]

Time	Percentage gain in weight at various relative humidities							
	At 86 percent		At 94 percent		At 97 percent		At 100 percent	
	Static	Flowing	Static	Flowing	Static	Flowing	Static	Flowing
Days	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
¼	0.4	0.5	0.7	0.6	1.1	1.0	1.7	0.8
⅛	1.0	1.0	1.7	1.5	2.5	2.4	3.7	2.2
¼	1.7	1.7	2.7	2.6	4.1	4.2	5.8	3.9
1	4.2	4.6	7.3	7.1	10.7	12.0	12.8	12.3
3	7.4	7.7	14.4	13.9	21.3	23.9	24.4	26.0
7	8.9	9.0	19.4	19.7	33.1	37.2	40.0	42.5
14	9.4	8.9	23.6	21.6	45.1	44.8	57.7	57.0

With the foregoing data as a basis of calculation of the moisture absorption of the coated fabrics that are used on an airship of the GZ–1 type such as the *Macon*, the values for gain in weight after 1 day, 1 week, and 4 weeks have been obtained and are presented in table 18. The outer cover data are calculated from the results given in tables 2, 5, and 11, those for the lightweight and heavyweight, gas cell fabrics from tables 13 and 14, respectively. The data for

the lightweight fabric are on the basis of the sample containing 0.7 oz/sq yd paraffin or 14 percent by weight; those for the heavyweight fabric are on the basis of the sample containing 0.6 oz/sq yd paraffin or 9.5 percent by weight. It will be observed that the gain in weight in 1 day at the high humidities is approximately 1 ton; after 1 week it varies from 1.5 to 3.25 tons and after 4 weeks from 2.5 to 6.75 tons. A comparison of the figures in table 18 with those that Bird [11] calculated for the British dirigible *"R.100"* is interesting. He calculated that the scheduled weight of the gas bags on the *"R.100"*, namely, 7.3 tons, might increase 70 percent in weight or 5.1 tons, according to his experimental data; he likewise noted that the scheduled weight of the outer cover, namely, 4.35 tons, might be increased by not more than 1 ton. This makes a net increase of 6.1 tons. The higher value noted in table 18 is due to the larger size of the airship and to the greater hygroscopicity of the fabrics.

TABLE 18.—*Gain in weight (pounds) of the fabrics used on an airship (GZ–1 type) at various humidities*

Materials	Weight at 65 percent relative humidity and 21° C	Gain in weight at various relative humidities								
		At 94 percent relative humidity			At 97 percent relative humidity			At 100 percent relative humidity		
		1 day	1 week	4 weeks	1 day	1 week	4 weeks	1 day	1 week	4 weeks
	lb	lb	lb	lb	lb	lb	lb	lb	lb	lb
Outer cover	11, 680	526	526	526	748	853	853	1, 016	1, 834	3, 247
Gas-cell fabric, lightweight	11, 163	513	1, 764	2, 891	737	2, 735	5, 570	815	3, 260	6, 955
Gas-cell fabric, heavyweight	7, 171	280	925	1, 556	337	1, 241	2, 868	351	1, 406	3, 227
Total	30, 014	1, 319	3, 215	4, 973	1, 822	4, 829	9, 291	2, 182	6, 500	13, 429

V. SUMMARY AND CONCLUSIONS

1. Aircraft fabric doped with cellulose nitrate absorbs only small amounts of water at high humidities; the gain in weight noted in a saturated atmosphere was less than 12 percent of its weight in the standard conditioning environment, 21° C and 65 percent relative humidity.

2. Aircraft fabric doped with cellulose acetate behaves similarly to fabrics coated with cellulose nitrate dope at relative humidities as high as 97 percent. At 100 percent relative humidity the cellulose acetate product is more hygroscopic and absorbs about 20 percent of moisture in 1 week and 40 to 55 percent of moisture over a period of weeks.

3. Gas-cell fabric, that is balloon cloth coated with gelatin-latex plasticized with polyglycerol, is exceedingly hygroscopic and is capable of approximately doubling its weight at 100 percent relative humidity in 4 weeks. The rate of absorption is retarded considerably by paraffin which is always applied to the surfaces of the gas-cell fabric in service.

4. Unparaffined gas-cell fabric loses absorbed moisture comparatively rapidly when the relative humidity of the atmosphere is

[11] J. Roy. Aero. Soc. **35**, 973 (1931).

decreased, whereas the paraffined material requires approximately the same period for the desorption as for the absorption of moisture.

5. The gas-cell fabrics have been found to be susceptible to attack by mold at 21° C and relative humidities from 94 to 100 percent, inclusive. It is desirable that a fungicide be added to fabrics with the gelatin-latex coating in order to prevent the deterioration of the finished product by mold action.

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